

A Hierarchical Modeling Methodology for the Definition and Selection of Requirements

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A Hierarchical Modeling Methodology for the Definition and Selection of Requirements

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LIST OF ACRONYMS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AoA	Analysis of Alternatives
BOCR	Benefits, Opportunities, Costs and Risks
CAD	Computer Assisted Design
CDF	Cummulative Distribution Function
CDF	Cummulative Distribution Function
C.I.	Consistency Index
CONOPS	Concept of Operations
C.R.	Consistency Ratio
DFA	Design For Assembly
DoD	Department of Defense
DOE	Design of Experiments
DP	Design Parameter
FFD	Functional Flow Diagram
FMEA	Failure Mode and Effects Analysis
FR	Functional Requirements
GAO	General Accounting Office
HALE	High Altitude Long Endurance Aircraft
HALE	High Altitude Long Endurance
HoQ	House of Quality
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering

IPPD	Integrated Product and Process Development
IRMA	Interactive Reconfigurable Matrix of Alternatives
ISO	International Standards Organization
LCC	Life Cycle Cost
LH2	Liquid Hydrogen
LP	Linear Programing
MADM	Multi-Attribute Decision Method
MC	Monte-Carlo
MOE	Measures Of Effectiveness
MOP	Measures Of Performance
NASA	National Aeronautics and Space Administration
NFR	Non-Functional Requirement
PDF	Probability Density Function
PEM	Proton Exchange Membrane
PMAD	Power Management And Distribution
QFD	Quality Function Deployment
RFP	Request For Proposal
R.I.	Random Consistency Index
RSE	Response Surface Equation
RSM	Response Surface Methodology
RSM	Response Surface Methodology
S.I.	Compatibility Index
SA	Sensitivity Analysis
SEP	Systems Engineering Process

SoS	Systems-of-Systems
SysML	System Modeling Language
TPM	Technical Performance Measure
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UML	Unified Modeling Language
UTE	Unified Tradeoff Environment
VSP	Vehicle Sketch Pad
WBS	Work Breakdown Structure

SUMMARY

This dissertation describes the development of a requirements analysis methodology that takes into account the concept of operations and the hierarchical decomposition of aerospace systems. At the core of the methodology, the Analytic Network Process (ANP) is used to ensure the traceability between the qualitative and quantitative information present in the hierarchical model. The proposed methodology is implemented to the requirements definition of a hurricane tracker Unmanned Aerial Vehicle.

The purpose of the methodology is to allow traceable identification and definition of complex systems requirements. Three research objectives are identified to achieve this purpose; (1) improve the requirements mapping process by matching the stakeholder expectations with the concept of operations, systems and available resources; (2) reduce the epistemic uncertainty surrounding the requirements and requirements mapping; and (3) improve the requirements down-selection process by taking into account the level of importance of the criteria and the available resources.

A study performed by the Standish Group and published by Scientific American in 1994, has established that around 22% of project failures in complex systems can be attributed to incomplete and changing requirements. Several challenges are associated with the identification and definition of requirements. The complexity of the system implies that a large number of requirements are needed to define the systems. These requirements are defined early in the conceptual design, where the level of knowledge is relatively low and the level of uncertainty is large. The proposed methodology intends to increase the level of knowledge and reduce the level of uncertainty by guiding the design team through a structured process.

To address these challenges, a new methodology is created to flow-down the requirements from the stakeholder expectations to the systems alternatives. A taxonomy of requirements is created to classify the information gathered during the problem definition. Subsequently, the operational and systems functions and measures of effectiveness are integrated to a

hierarchical model to allow the traceability of the information. Monte Carlo methods are used to evaluate the variations of the hierarchical model elements and consequently reduce the epistemic uncertainty. The proposed methodology is applied to the design of a hurricane tracker Unmanned Aerial Vehicles to demonstrate the origin and impact of requirements on the concept of operations and systems alternatives.

This research demonstrates that the hierarchical modeling methodology provides a traceable flow-down of the requirements from the problem definition to the systems alternatives phases of conceptual design. A taxonomy of requirements should be used to store and manage the information throughout the requirements analysis process. The ANP provides a common framework to ensure the traceability of the information while allowing uncertainty analysis and requirements down-selection. The analysis of systems alternatives is also integrated into the ANP to provide quantitative information used to define threshold and goal objectives during the creation of the requirements statements.

Chapter I

INTRODUCTION

1.1 Motivation

This thesis is about the creation of a methodology, appropriate for conceptual design, including the definition, modeling and selection of requirements for the design of complex systems. Complex systems like Unmanned Aerial Vehicles (UAV) are challenging to design because of the large number of potential configurations, mission profiles, integrated systems and technologies [133]. Lack of historical data, growing market demand and increasing system complexity make UAV an ideal design application for the proposed methodology.

In 1998 the revenue of the global UAV market was \$2.07 billion. In 2008 the forecast for the same market is \$6.87 billion, a growth of 300% in ten years [72]. In 2003, another source stated that the market for UAVs performing reconnaissance and surveillance missions is expected to be worth more than \$10 billion over the next decade [98]. The visibility and success of UAV military applications in Afghanistan and Iraq has greatly contributed to the market growth. The U.S. Department of Defense (DoD) justifies the need of UAVs over manned aircraft when a mission includes operations that can be qualified as “dull (long duration)”, “dirty (sampling of hazardous material)” or “dangerous (extreme exposure to hostile action)” [139]. The same justifications can also be applied for civilian applications like communication relay station, hurricane tracker, forest fire detection, or search mission in a hostile environment. Most of these notional applications involve the use of new technologies. The ability to test and integrate new technologies is a major factor in the expansion of the UAV market. For instance, the increase in fuel price favors a push toward more electric aircraft. In this context researchers are trying to use fuel cell systems for primary and secondary sources of power [64, 126]. Technology demonstrator UAVs can also be used to perform extra planetary missions, like the NASA UAV platform ARES, designed to survey the Martian surface [196]. Therefore, as the UAV market is expanding, so is the complexity

of the new systems.

In this study a UAV requirements analysis will be used as an example application of the proposed methodology. This complex system was selected due to the large design freedom surrounding the UAV conceptual design process. The objectives of this chapter are to (1) introduce the reader to the research scope, (2) define the purpose statement of this work and (3) layout the organization of the thesis.

1.2 Research Scope

In its most fundamental sense, a requirement describes a characteristic that must be performed by a process, system or component. Requirements analysis in conceptual design is a very large field of research. This section is tailored to bind the thesis scope by focusing on specific areas of research.

A general requirements analysis process, illustrated in Figure 1.1, is divided into the customer and engineering domains. Requirements represent a common language connecting these domains. On the one hand, customers express needs, desires and capabilities to engineers. On the other hand, engineers help the customers to select the appropriate systems, performance and technology to answer their needs. As the systems become more complex the number of needs, desires and requirements increase dramatically. On the engineering side of Figure 1.1, systems engineering, quality engineering, system modeling and life cycle analysis (grey blocks) represent some of the fields influencing this research. The primary research areas (blue blocks) addressed by this thesis are requirements mapping, uncertainty analysis, requirements selection and resource allocation. The outputs of the process are then used toward the selection of the system alternatives.

The “*iterative and evolving process*” loop emphasizes the iterative nature of the requirements analysis process. As stated by Loucopoulos and Karakostas: “*a requirements specification cannot be developed in a simple linear fashion; a cyclic approach which gradually yields an involving specification seems to be more appropriate*” [107]. During the conceptual design analysis, the design team through the sizing and synthesis of the system elicits new information. The sizing process scales the physical dimensions of the systems, while the

synthesis process uses these dimensions in multi-disciplinary tools to calculate the vehicle's performance. During this process, requirements and constraints are identified and fed-back to the requirements analysis process in order to create verifiable and achievable requirement statements.

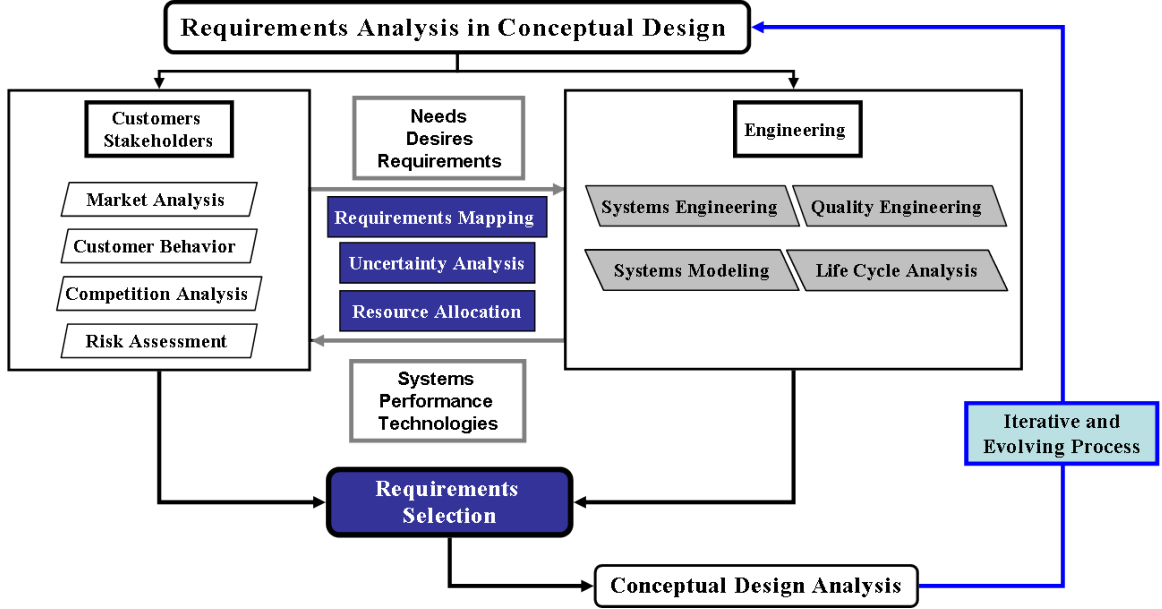


Figure 1.1: Research areas included in thesis scope.

To further describe the primary research areas, this section first introduces the concept of requirements and design. The second section describes the importance of this work for the aerospace and systems engineering communities. The third section discusses current problems related to requirements methodology, and the last section describes the limitations of this work.

1.2.1 Introduction to Design and Requirement

The design of a new product is a challenge that requires the synthesis of creativity, technical skills and decision making. The origin of an innovative concept may come from a brilliant idea or from an organizational need, however its realization is the outcome of a thorough design process. Design can be defined as follows: “the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs (Functional Requirements) in the functional domain and the DPs (Design

Parameters) of the physical domain, through the proper selection of DPs that satisfy FRs” [165].

Typically, the design process is divided into three majors phases: conceptual, preliminary, and detailed design as shown in Figure 1.2. In this figure, the design process is initialized by

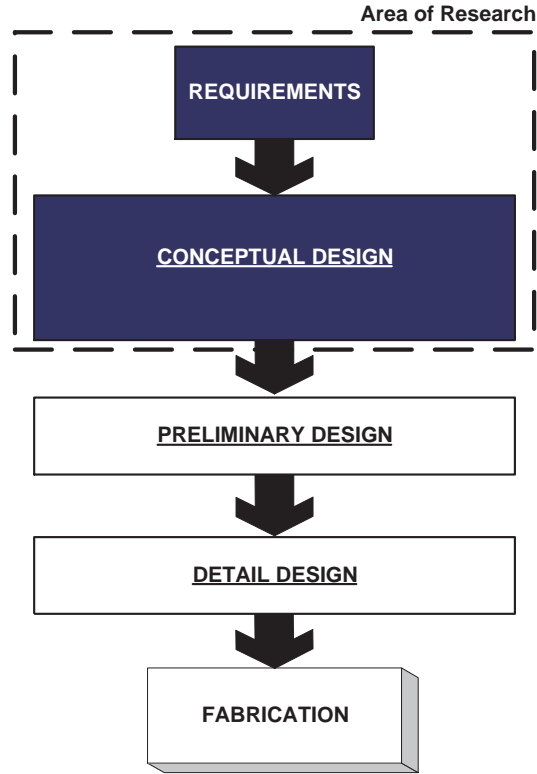


Figure 1.2: Traditional design process. Modified from [145].

a set of requirements, and it is completed by the fabrication of the system. In between, all the activities have an important impact on the quality and robustness of the final product. The requirements represent a bridge where information is transferred from the customers to the engineers and vice versa.

The fundamental purpose of requirements is to capture the customer’s needs in a statement that can be used to derive alternative solutions. Requirements are the cornerstone of this thesis, at this stage it is important to establish a more formal definition. The International Council on Systems Engineering (INCOSE) defines requirement as follow [83]:

*“**Requirement:** A statement that identifies a system, product or process characteristic or constraint, which is unambiguous, can be verified, and is deemed necessary for stakeholder acceptability .”*

This definition emphasizes the importance of requirements mapping and uncertainty analysis, which are introduced in Figure 1.1. Requirements must be mapped to stakeholders and systems; these terms are described in Chapter 2. The requirement & stakeholders relationships are essential to determine the system level of achievement, while the requirement & systems relationships are used to determine the influence of requirements on the systems, and consequently enabling a verification process. The verification process requires the requirements to be as unambiguous as possible, therefore implying some uncertainty analysis. Sources of ambiguity include requirement semantic, incomplete information, incomplete knowledge and conflicting requirements. Conflicts or trade-offs occur mostly during the requirements allocation and selection processes.

Every industrial project has a limited amount of resources in the form of money, knowledge, technology development and time [181]. Consequently, strategies are created to allocate resources in order to assure the success of the project. In the case of a complex system, assuming a very large number of requirements, it becomes difficult to allocate resources because it implies that some requirements might not be fully achieved and consequently some stakeholders will not be satisfied [180]. This problem leads to the requirement selection process.

The requirement selection process must take into account the importance of the stakeholder, the level of uncertainty, the resource needed and the impact of the requirements on the system. The process gets more complex by considering multiple levels of requirements. There are top-level requirements, attributed to main systems, all the way to sub-system requirements. The cruise Mach number is an example of top-level requirement attributed to the aircraft system, while the main landing gear stroke length is an example of sub-system requirement. This process is complex, because the stakeholders not only impact the selection of requirements but also impact other stakeholders. The same can be said about requirements and resources, their influences are spread throughout the life cycle of the system.

Consequently, the problem needs to be structured in order to decompose and understand the complexity.

This section introduced the main research areas, requirements mapping, uncertainty analysis, resource allocation and requirements selection. The next section discusses the importance of these research areas on the requirements analysis process and more importantly the impact on the system life cycle.

1.2.2 Importance of an Improved Requirements Analysis

The importance of an improved requirements analysis process is based on two premises; first by understanding the influence of requirements in the success of a project; and second by gauging the interests of the industry in improving the current processes.

The analysis of the requirement's importance in the success of a project implies the definition of a successful project and the evaluation of the impact of requirements on the system. A General Accounting Office (GAO) report, in the series on best practices, describes that the key for a successful project is to match project needs and resources [180]. To achieve this goal, it is suggested to make early trade-offs between the product design and the customer's expectations. This reasoning leads to the requirements process illustrated in Figure 1.3. This figure shows that the path toward product requirements goes through the matching of resources with expectations. The figure has been modified by adding the primary research areas of this thesis, and depicting where they intervene in this process.

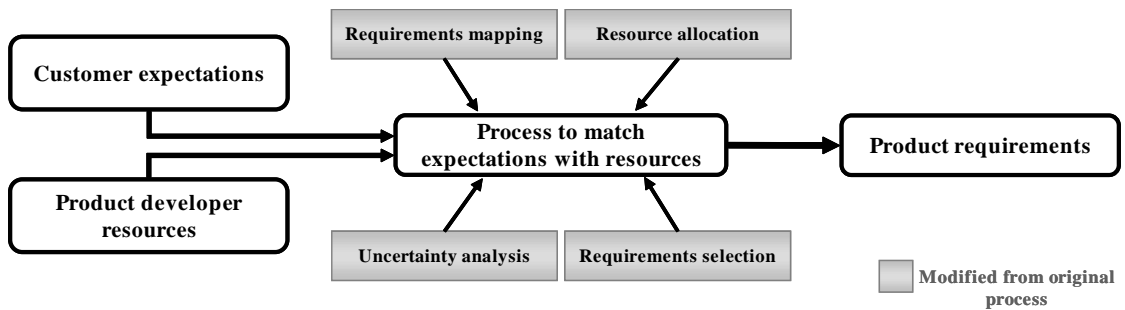


Figure 1.3: GAO - Requirements process. Modified from [180].

The importance of matching customer expectations and resources is connected to the project committed costs during conceptual design. As emphasizes by Loucopoulos [107]:

“... [requirements engineering] is arguably the most crucial activity in system development, if only because errors made in the early requirements specification phases are the most costly to repair once the system has been implemented”.

The relationship between life cycle cost versus time is illustrated in Figure 1.4. This historical relationship shows that approximately 70% of the life cycle cost is committed during the concept selection. Consequently, any error made at the stage has a large impact on the project costs [83]. Furthermore, the same figure depicts another relationship between the cost to extract defects and time. In other words, if the system changes during the design process it becomes more expensive to implement the modifications. The best time to make modification is at the concept level, which emphasizes the need to elicit the “right” requirements in order to minimize the extra cost of modifying the systems.

In summary, a successful project needs to match the customer’s expectations with the available resources at the front end of the design process. The most important expectations are then transformed into functions and finally into requirements. For complex systems the number of requirements is very large, consequently it is difficult for decision makers to make the right decisions, early in the process, in order to reduce unnecessary expenses. In this context, requirements play an important role because they “... drive the amount of capital, time, expertise, and technologies the developer must invest” [180]. Requirements are also used throughout the product life cycle, however their role is emphasized toward the beginning and the end of the design. This work focuses on research areas that will provide more information to the decision makers and help them during the requirement definition and selection process.

The second part of this section discusses the interests of the industry in having an improved requirements analysis process. Due to the fact that complex systems represent enormous financial risk for an enterprise, there is a tendency to mitigate the risk by contracting parts of the system. The following statement by Eric C. Honour, INCOSE Founder and former INCOSE President, underlines the impact of this acquisition dynamic on the requirements [76]:

“If someone is trying to contract for a system, and they can properly identify

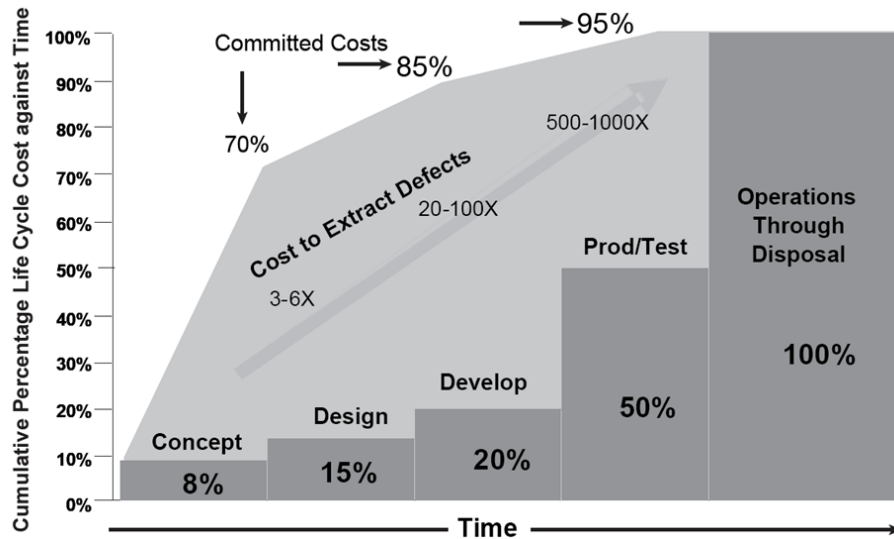


Figure 1.4: Committed life cycle cost versus time. Source [83].

all the necessary requirements, then it makes sense to do so. The preference then usually becomes: “Meet the requirements, and pick the lowest cost.” But the reality is, in every complex system I’ve seen, most ‘requirements’ aren’t. Given the right combination, nearly any requirement will be relaxed to obtain some other gain. The real preferences are hidden behind the requirements in some operational analysis space.”

This statement describes the difficulty of meeting requirements during the design of a complex system. As pointed out, some requirements need to be relaxed so that other requirements can reach their threshold. It illustrates the importance of matching the customer’s expectations by either relaxing the requirements and/or the expectations. The second part of the statement discusses the DoD acquisition reform initiatives. It says the requirements selection is based on “some operational analysis space”. This could be translated into specific system capabilities. Capability based design implies that engineers are given capabilities to meet and not necessarily requirements or needs. However, this additional complexity does not change the fundamental problem of matching the customer’s expectations. This new acquisition reform underlines that many stakeholders are impacted by the outcome of the requirements selection process. Ultimately government, main contractor (integrator), sub-contractors, taxpayer and end-users are all impacted by decisions made early in the project design.

1.2.3 Current Requirements Analysis Gaps

The gaps of the current requirements analysis methodologies revolve around the understanding of the customer’s expectations, which leads to the second gap of understanding the requirements uncertainty.

Expectations and needs are difficult to evaluate at the beginning of the project because of the many directions that the project can take. Even from the customer perspective, it is difficult to define their desires knowing that they do not have extensive knowledge about existing systems without taking into account new technologies and revolutionary systems. Assuming this fact, it is predictable that as the customers become more knowledgeable about the system’s capabilities, their expectations may evolve in another direction. There are a lot of new products that fail to reach their intended market as stated in this quote by Hsiao [77] based on a study by Booz et al.[21]:

“... the failure rate of new products actually introduced in the market remained in the 33-35% range between 1963 and 1981.”

Another study has indicated the role of requirements in project failures of complex systems in the software industry. The results of this study are depicted in Table 1.1. Even though there are requirement analysis methodologies already in place, a large percentage of project failures are attributed to requirements.

Table 1.1: Reasons for project failures. Source [79].

Incomplete requirements	13.1%
Lack of user involvement	12.4%
Lack of resources	10.6%
Unrealistic expectation	9.9%
Lack of executive support	9.3%
Changing requirements/specifications	8.7%
Lack of planning	8.1%
Didn’t need it any longer	7.5%

Sources: Standish Group 1995 and 1996

Scientific American, September 1994

From Table 1.1, it can be seen that around 22% of project failures are directly linked to requirements, incomplete and changing requirements. Specific reasons connected to these

requirement categories are: “... *poorly organized, poorly expressed, weakly related to users, changing too rapidly, or unnecessary, unrealistic expectations*” [79]. Several of these reasons can be regrouped under incomplete mapping between requirements, stakeholders and systems. In a study on design changes, Jordan et al. listed the following reasons for changing requirements [86]:

1. Hardware failure;
2. Obsolescence;
3. Hardware upgrade;
4. Goal change.

The Lockheed AH-56 Cheyenne helicopter, shown in Figure 1.5, is an example of project failure due to changing requirements and more specifically to changing goals [140]:

“The failure of these two aircraft (referring to the Lockheed AH-56 Cheyenne and the Sikorsky S-67 Blackhawk) is linked that they were both designed around a customer requirement that was ultimately decided to be flawed. The demise of the specification was due in part to financial considerations and changing Army requirements ...”



Figure 1.5: Lockheed AH-56 Cheyenne helicopter. Source [73].

The financial considerations were due to the Vietnam War, while the changing requirements were caused by political pressure coming from the Air Force. The Air Force felt that the Cheyenne helicopter was stepping into their field of operations, because of its speed and long range. The AH-56 Cheyenne project was canceled after six years of research and development, which cost approximately \$400 million in 1972. This example also shows how much risk is involved in the development of a complex system. The following statement summarizes the first gap in requirements analysis:

Observation 1: Incomplete and changing requirements can be attributed to improper matching between customer’s expectations, requirements, available resources and the system.

The second gap in the requirements analysis process is caused by the presence of uncertainty. This problem is well known in the industry and research as supported by this statement [18]:

“... product requirements in the early stages may be poorly understood leading to work on the basis of vague assumptions”.

Uncertainty has many forms, it can be associated with the market demand, customer expectations, system complexity or even the lack of the system knowledge. The analysis of the market demand is outside the scope of this thesis, however results from market analysis can be used in the proposed methodology.

The customers are also a source of vagueness due to the language and semantics used to define the requirements. When a project starts, the customer describes his needs and requirements by using his own words. For instance, the customer may tell the engineer that he wants *light* engines for his aircraft. In that context what does *light* mean, is it 500 kg or 5000 kg? Clearly the concept of “light” is imprecise and vague. The design team must then use this vague requirement within its formal and well-structured analysis codes. Since “light” is not a common input of the engine sizing tool, engineers will have to make assumptions with respect to the requirement’s definition.

Another source of uncertainty related to customers is the definition of satisfaction. The problem becomes more complex when systems involve multiple customers. How to declare

a project successful based on the level of satisfaction of multiple customers? Are some customers more important than others, which would make their expectations more or less important? These are questions difficult to answer, and they are part of this research scope.

The last main source of uncertainty is the lack of system’s knowledge. Complex systems include many sub-systems of different levels; for instance a landing gear is an aircraft system, and the brake assembly is a sub-system of the landing gear. Since requirements exist at every level, the potential number of requirements is very large. Assuming that engineers and decision makers have incomplete knowledge about the system, it is almost certain that requirements will be inaccurately defined or even left aside.

In current requirements analysis processes the uncertainty is generally captured by decomposing the project in hierarchy and by assuring the traceability between the different levels as shown in Figure 1.6. This figure shows the “Vee” diagram, this process is meant to

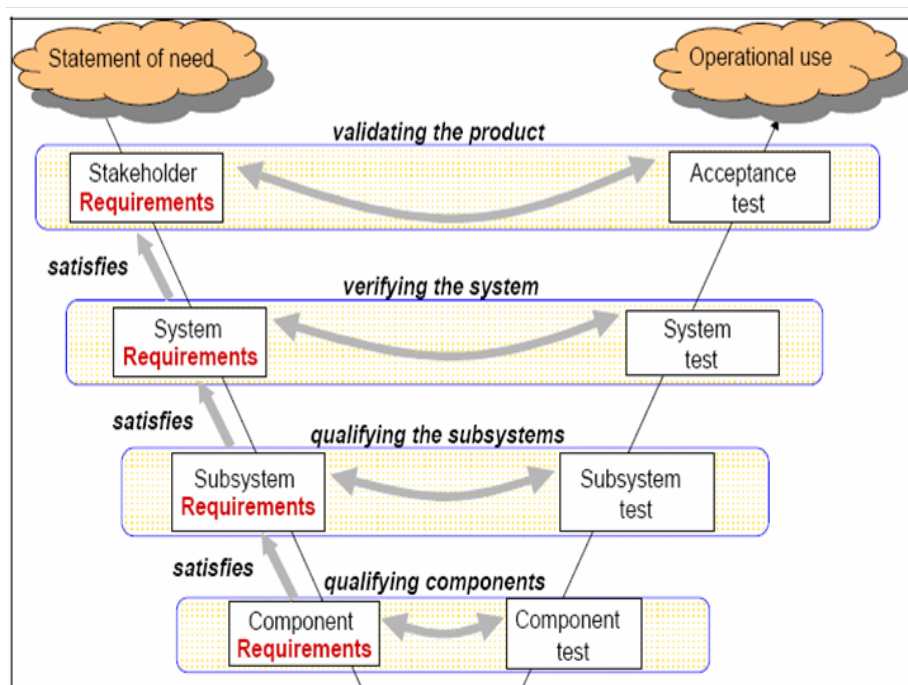


Figure 1.6: System engineering “Vee” diagram. Source [44].

decompose the problem in level from general need to specific requirements (Top-Down), and then verifying the system from specific components to mission applications (Bottom-Up).

This process creates a need for additional formality in the systems modeling and requirements analysis field, which opened the path for new programming languages like Unified Modeling Language (UML) and System Modeling Language (SysML) [179, 168]. These languages led toward the creation of new software programs to manage and trace requirements; for example Telelogic DOORS is one of the most popular requirements management and systems modeling software [172]. One of the advantages of Telelogic DOORS is to provide traceability between requirements of the same or different levels. Consequently, it is possible to assess the impact of design changes to every level of the requirement framework.

Important observations from the second requirements analysis gap are formalized in the following statement:

Observation 2: There are multiple sources of requirement uncertainty, and it has been observed that assuring the traceability between stakeholders, requirements, resources and systems tends to reduce the uncertainty.

The third gap in the requirements analysis process is related to the down-selection of requirements. For a complex system with limited resources it is difficult, if not impossible, to equally satisfy all requirements. Hence, the objective is to reduce the number of requirements by taking into account the impact of requirements on stakeholders, systems and resources. However, there are inherent limitations to that process. Psychological experiments have shown that the human brain’s discrimination ability and short-term memory is limited when comparing alternatives. In one of these experiments, James Martin stated the following [114]:

If a individual “has to choose from a range of 20 alternatives, he will give inaccurate answers because the range exceeds the bandwidth of his channel for perception. In many cases, seven alternatives are the approximate limit of his channel capacity.”

Therefore, considering a large initial number of requirements, this limitation creates a significant obstacle during the down-selection process. One potential solution is to regroup requirements in categories, and then to compare a smaller subset of requirements. This

solution does not resolve the entire problem, since the following questions still need to be answered:

- i. How to regroup requirements?
- ii. How to determine the importance of requirements?
- iii. What are the criteria used for the requirement down-selection?
- iv. What are the relationships between the requirements in different groups?

Groups of requirement are created based on their interactions with the system functions, system components and stakeholders; for instance there are performance (system) requirements and derived (stakeholder) requirements. It is important to establish clear definitions for every group of requirements in order to facilitate the classification and to organize the requirements in a structured manner.

The organization of requirements leads to the determination of the requirement's importance. One can imagine a hierarchy of requirements starting from general (i.e., the aircraft shall takeoff) to specific (i.e., the wing deflection shall not exceed 1m), and wonder if all requirements are equally important or if the importance varies depending on the requirement's level in the hierarchy. Also does it make sense to compare requirements from different levels of the hierarchy?

Current tools such as functions and systems hierarchies are used to organized the information gathered during the requirements analysis process. The hierarchies are constructed in order to allow comparison between components of the same level. The same type of hierarchy can be constructed with the different groups of requirement. Consequently, the requirement's importance could be assessed by taking into account the requirement's level in the hierarchy, and the requirement's relationships with the functions, systems, customers and resources. However integrating functions and systems hierarchies in the requirements down-selection is not an easy task due to the large number of complex interactions between requirements, functions, systems and resources.

The next step is to establish criteria to down-select the requirements. The selection criteria should relate to a customer satisfaction model. However, an acceptable level of customer satisfaction is not simple to define, because complex systems imply many interactions between customers and requirements. Current methods such as the Quality Function

Deployment (QFD) process help to down-select the number of requirements based on relationships between requirements and engineering characteristics [65]. In this process, the number of relationships to define is often much greater than the previously mentioned brain channel capacity, which generally allows consistent comparison if the number of items is smaller than seven. Furthermore, the QFD down-selection does not take into account requirement's relationships with stakeholders and resources.

Observations from the requirements down-selection process are summarized as follows:

Observation 3: A clear definition of the different types of requirements is needed to start the down-selection process. A structured approach is required to classify the requirements and to map them with the functions, systems, stakeholders and resources. A model of customer satisfaction can be created based on these relationships and a set of selection criteria such as benefits, costs and risks.

1.2.4 Limitations

The previous sections defined the general scope of this research, but it is also important to define the scope limitations. The description of these limitations is meant to clarify ambiguity and/or questions that might have occurred in the reader's mind up to this point. The limitations are focused on the UAVs applications, the type of requirements and the type of analysis surrounding the proposed methodology.

This study does not include demand and market analysis of UAV systems. The proposed requirements analysis methodology assumed that the market analysis has already been established for a given type of UAV, and that requirements, capabilities or needs are transferred to the engineering team. It is important to mention that the transferred set of requirements is not considered static, but has the flexibility to evolve as new information becomes available in the process.

The emphasis of the proposed methodology is on conceptual design requirements, not detailed design or manufacturing requirements. Consequently, the types of requirements revolve around performance, operational, regulatory and corporate requirements. The requirements analysis is limited to system and major sub-system requirements. For example,

there is no detailed requirements analysis performed on sub-systems such as hydraulics requirements for the landing gear brake.

As mentioned in the research scope, section 1.2, the main research areas are requirements mapping, uncertainty analysis, resource allocation and requirements selection. Some of these research areas may involve risks and technology analysis, however it is not the primary focus of this thesis to perform detailed risk and technology assessment of the different vehicle alternatives. The objective of the proposed methodology is to provide more information to perform these types of analyses.

1.3 Purpose Statement

The previous sections established the need to improve the current requirements analysis process through the identification of gaps in current methods. Furthermore, the research scope has been bounded by describing the main research areas, and by defining the thesis limitations for areas outside the scope boundary. The objective of the purpose statement is to succinctly summarize the intent of the work. The purpose statement of this thesis is:

The purpose of this thesis is to create a design methodology allowing the definition and modeling of complex systems requirements.

To substantiate the purpose statement, the following research objectives are established based on the observations made in the previous sections:

Objective 1: Improve the requirements mapping process by matching stakeholder expectations with functions, systems and available resources. The requirements mapping should also help the transition between qualitative and quantitative analyses.

Objective 2: Reduce the requirements uncertainty by having a structured approach allowing requirements traceability in the mapping. The uncertainty shall also be reduced by taking into account the brain channel capacity limitation, which also has an impact on the consistency during relative comparison.

Objective 3: Improve the requirement selection process by taking into account established criteria and available resources. The resources can include tangible (money) and intangible (risks, safety) aspects.

The last two objectives summarize important concepts established in previous section, while the first objective introduces a new concept of transition between qualitative and quantitative analysis. Fundamentally, the requirements analysis process is both qualitative and quantitative. Qualitative analysis results from a synthesis of expert judgments on the systems, while quantitative analysis is based either on historical data or on physics-based models. It is difficult to transfer the knowledge obtained during the qualitative analysis in a quantitative environment. For example, assume that safety is an important requirement for the vehicle, and that experts have established qualitative relationships between safety and some systems characteristics. If there is no safety model, how can one quantify the safety impact on the customer satisfaction model? The proposed methodology has an objective to smooth this transition by using the qualitative results in the quantitative environment.

The customer's expectations are the primary inputs to the proposed methodology, while the main outcome is a set of requirements that drives the design of the complex system in the next life cycle stage. This set of requirements is based on complex mapping between requirements, systems and resources. The traceability between these components is also an important aspect of the methodology. For instance, a customer could decide to dynamically modify some mapping and observe the impact of these changes on the down-selection of requirements and the committed costs. All the new information should help the customers and design team to make better decision and therefore improve the chance of project success.

1.4 Organization of the Thesis

The outline of this research is mapped with the milestones illustrated in Figure 1.7. The thesis milestones are based on the premise of the scientific method. Chapter 1 introduces the thesis topic while bounding the research scope by defining research objectives. Chapter 2 defines the problem further by analyzing current requirements analysis methodologies in order to identify problem areas. Chapter 3 includes the literature review of processes

and tools having the potential to improve gaps identified in Chapter 2. In Figure 1.7, the literature review is represented as the background of the thesis milestones in order to emphasize the fact that every step requires some background research. Chapter 4 presents the research questions coming from the problem definition, and the hypotheses constructed from the knowledge acquired during the literature review. Chapter 4 also describes the proposed methodology that is meant to answer the research questions. Chapter 5 describes two experiments used to explore the hypotheses stated in Chapter 4 by going through the steps of the proposed methodology. Finally, Chapter 6 concludes by revisiting the research questions and hypotheses and includes suggestions for future work that could further improve the current requirements analysis methodologies.

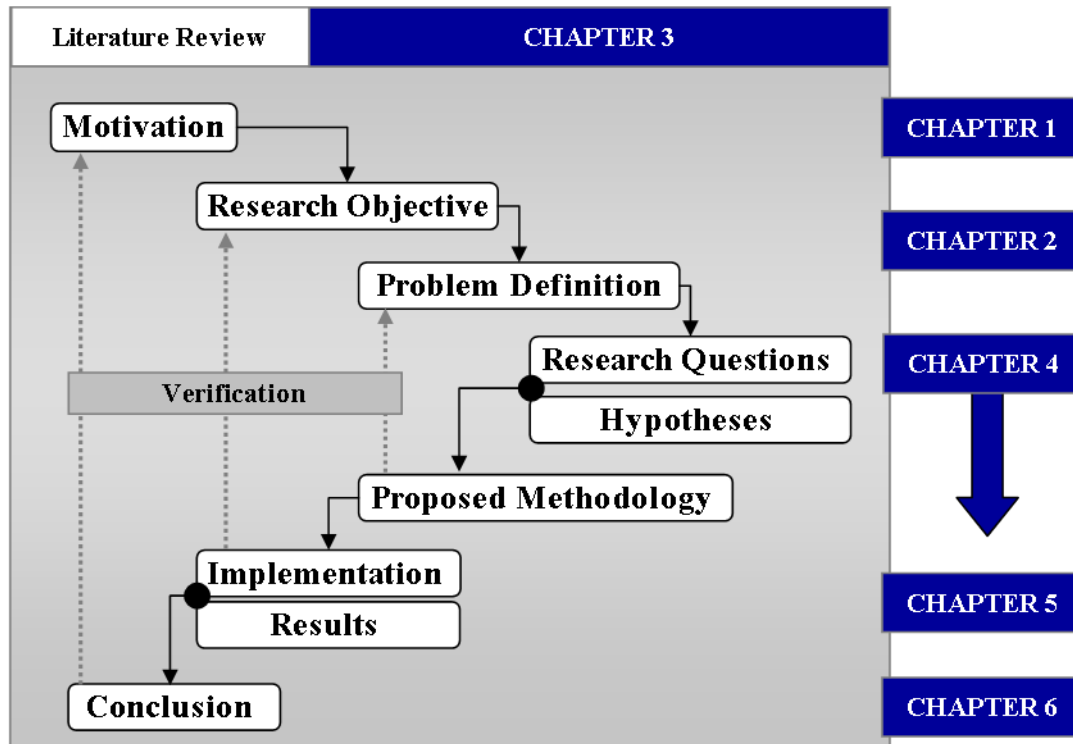


Figure 1.7: Thesis organization.

Chapter II

RESEARCH SCOPE DEFINITION

Every project starts with the system's requirements analysis. Due to the grand diversity of systems, the field of requirements analysis has spread out into many different system specific methods and processes. Organizations such as INCOSE, NASA, DoD and IEEE have created their own systems engineering handbooks including their own requirements analysis methodology. The purpose of this thesis is to build on current requirements methodologies and improve current deficiencies and gaps of their applications to complex systems design.

This chapter intends to further narrow the research scope by pursuing two objectives. The first objective is to define requirement's terminology used throughout this research. The second objective is to determine the origin of the current methodology gaps observed in section 1.2.3. The achievement of these objectives is essential to guide the literature review of this thesis.

2.1 Definition of Important Concepts

The concept of requirement is used in many different fields, each of these fields often have different definitions for the same terms. The goal of this section is to define a common terminology for stakeholders, requirements and systems, since these terms represent the core of the proposed methodology.

2.1.1 Definition of Stakeholder

One of the key concepts mentioned in Chapter 1 is the stakeholder. In systems engineering stakeholders are defined as follows [83]:

“A party having a right, share or claim in a system or in its possession of characteristics that meet that party's needs and expectations.”

From this definition, stakeholders may imply a large number of the people with direct or indirect interactions with the product during its life cycle. For instance the main stakeholder

of a car is the owner. However if the car is financed, then the car dealership and the financing party are also stakeholders. Pushing this example even further, car mechanics are also stakeholders because of their numerous interactions with the system during its operating life. From this example, it is possible to imagine multiple levels of stakeholders depending on their interactions with the product. Figure 2.1 shows an example of multiple levels of stakeholders.

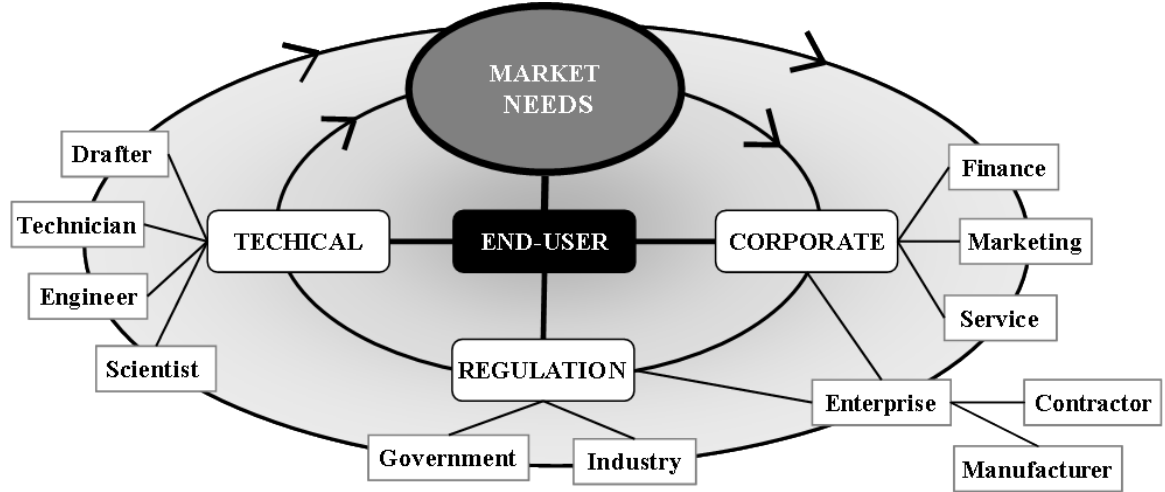


Figure 2.1: Categories of stakeholder.

The origin of every product or process development starts with the identification of needs from a given market. Figure 2.1 shows a direct connection between the market and the end-user. End-users represent the party of people having direct interactions with the product. In this research, the term customer is a synonym for end-user. The categories of stakeholders shown in Figure 2.1 are organized in levels depending on their interactions with the system. As the groups of stakeholders propagate outward, the more indirect their relations are with the system. However, that does not necessarily mean that their importance on the system is less than for more direct stakeholders.

The interactions between stakeholders and requirements are very important in establishing the success of a project. At the beginning of the design process, requirements are established based on needs or desires from one or multiple stakeholders. At the end of the design process, the product is judged successful based on the overall stakeholder satisfaction, which is an aggregation of every individual stakeholder satisfactions. The stakeholder's

satisfaction model is based on the initial needs and consequently the level of achievement of the requirements. The strong relationships between stakeholders and requirements are further described in the following definitions of the term requirement.

2.1.2 Definition of Requirement

In all the different engineering fields, there exist many definitions for the term *requirement*. Perhaps the most common definition of requirement is characterized by “what” the system or product must accomplish to fulfill specific stakeholder’s expectations. This section presents several definitions of requirement from various systems engineering sources. The objective is to have a clear understanding of what is a requirement, since it constitutes the primary concept of this research.

According to Jackson the term requirement is defined as follows [85]:

*“A **requirement** is a statement of required performance or design constraint to which a product must conform. One principle agreed on by many systems engineers is that a basic quality of a requirement is that it must be verifiable. The requirement is laid on the people, products, and processes, not on the engineer or the environment.”*

This definition implies that requirements are categorized in different types, such as performance and constraint. Also, well defined requirements must have certain properties such as being verifiable. Complete discussions on requirement’s properties and types of requirements are covered in sections 2.1.2.1 and 2.1.2.1 respectively.

The second definition is from the International Council on Systems Engineering [83]:

*“**Requirement**: A statement that identifies a system, product or process characteristic or constraint, which is unambiguous, can be verified, and is deemed necessary for stakeholder acceptability .”*

This definition also refers to key requirement properties. Furthermore, as mentioned in section 1.2.1, this definition emphasizes the requirements relationship with the stakeholders and the systems. Requirements are at the center of this relationship, they originate from

stakeholder's desires, and at the end of the design they are used to judge of the overall system performance.

The third definition is from Requirements Engineering. Requirements Engineering is a field of research established in the mid-1970s that deals with the development of software systems. As suggested by its name, requirements are the focal point of this discipline. With that regard, in 1985 the Institute of Electrical and Electronics Engineers (IEEE) provided a detailed definition for requirement, which is divided in three elements[81]:

- a) A condition or capacity needed by a user to solve a problem or achieve an objective;
- b) A condition or capacity that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents;
- c) A documented representation of a condition or capability as in 1 or 2.

Therefore, a requirement is a condition that relates a specific need or problem (item a) to a system or product (item b). Requirements must be well documented so that all the project participants (stakeholders), customers and design team, agreed upon which requirements drive the design. The same institution also established a definition for well-formed requirements [81]:

*“**Well-formed requirement:** A statement of system functionality (a capability) that can be validated, and that must be met or possessed by a system to solve a customer problem or to achieve a customer objective, and is qualified by measurable conditions and bounded by constraints.”*

From this definition, a well-formed requirement includes a *capability* defined by *conditions* and bounded by *constraints*. The following commercial transport aircraft example is meant to illustrate these concepts.

Requirement: The aircraft system shall be capable of moving people in regulated air space over a distance of 1000 nautical miles without refueling, at cruising altitude and Mach number of 30,000 ft and 0.8 respectively.

Capability: Move people over a finite distance.

Conditions: Range of 1000 nautical miles, altitude of 30,000 ft and Mach number of 0.8.

Constraints: Fuel required, flight path and altitude are subject to governmental regulation.

In this case, the requirement statement includes a lot of information to reduce potential ambiguity. The capability of the requirement corresponds to its fundamental function. Generally, a requirement only refers to one function. The functional analysis of requirements is discussed in more detail in Appendix A. The conditions or attributes of the requirements can be either qualitative or quantitative depending on the requirement. One must be careful not to include other requirements as conditions. For instance, the number of passenger is a requirement by itself, because it corresponds to the function “carry people”. The constraints impose boundaries on the potential solutions. A given constraint can be applied to more than one requirement, and other constraints can also represent stand-alone requirements; regulations are good examples of constraint requirements.

To summarize the previous definitions here are important aspects of requirements.

- Requirements bridge the stakeholder’s expectations with the system, product or process;
- Requirements are fundamental characteristics of a system, product or process;
- Different types of requirements are used for classification, and to decompose the problem complexity;
- There are properties to establish the goodness of requirements;
- Requirements must be well formed and documented.

2.1.2.1 Properties of Requirement

Multiple organizations in the systems engineering community have already established properties for requirements. This section defines and describes requirements properties identified by INCOSE, Department of Defense and IEEE. The properties are listed in Table 2.1. These properties have been regrouped in seven categories based on their definition. The categories are: (a) verifiable, (b) unambiguous, (c) traceable, (d) consistent, (e) abstract, (f) unique, and (g) complete.

Table 2.1: Requirements properties from INCOSE, DoD and IEEE

INCOSE [82]	DoD [43]	IEEE [81]
Verifiable (<i>a</i>)	Verifiable (<i>a</i>)	
Clear (<i>b</i>)	Unambiguous (<i>b</i>)	Bounded (<i>b</i>)
Traceable (<i>c</i>)		Linked set (<i>c</i>)
Consistent (<i>d</i>)	Consistent (<i>d</i>)	Consistent (<i>d</i>)
Abstract (<i>e</i>)	Abstract (<i>e</i>)	Granular (<i>e</i>)
Unique (<i>f</i>)		Unique (<i>f</i>)
	Complete (<i>g</i>)	Complete (<i>g</i>)
	Achievable	

A verifiable requirement is defined quantitatively so that it can be measured on the system at the end of the design process. The design team must try to eliminate qualitative requirements because they tend to create confusion and uncertainty. For instance, a customer may want to have a UAV that can fly “locally”; however the term “locally” is vague, and depending on the implied range the system design could be significantly different. In this case, the design team should evaluate the meaning of “locally” by defining a range satisfying the customer expectations.

The unambiguous property also relates to the subjectivity and vagueness of requirements. An unambiguous requirement should have one possible meaning in order to minimize the uncertainty. For performance requirements, the ambiguity is minimized by satisfying the verifiable property. However for other types of requirements, the level of uncertainty cannot only be reduced by assigning quantitative values. For example, if the customer wants the aircraft to be “safe.” It is difficult to define a single quantitative value for this requirement. Therefore the design team would have to define, with the customer, the term safety by assigning quantitative values such as maximum stresses or maximum accelerations. One way to reduce the ambiguity of requirements is to also satisfy the traceability property.

The traceability property implies a flow of information between stakeholders expectations, functions, requirements and systems. There are multiple levels of requirements, high-level requirements usually come from customer needs and functions, while lower level requirements are defined and managed by the design team. The traceability property is usually accomplished by defining a hierarchy or taxonomy of requirements. A top-down

approach can be used to define and trace requirements from high level, implying more general requirements, to lower level, implying more specific requirements. For instance the requirement that the UAV should fly “locally”, is a high level requirement coming from the customer. Based on this requirement, lower level requirements such as range, altitude, and speed can be formulated into a well-formed statement. As the number of levels and requirements increases, the probability of having conflicting requirements also increases. This aspect of the requirement definition is captured with the consistency property.

A requirement must be consistent with the customer expectations it is meant to achieve. Unnecessary requirements add uncertainty in design, and they can divert precious resources during resource allocation. Consistency also implies the management of conflicts and trade-offs. The design team should try to understand the source of conflicts and create strategies to mitigate them. Doing so provides valuable information to the decision makers during the concept down-selection. That being said, a requirement definition should not be biased toward a specific concept or solution. This characteristic refers to the abstraction property of requirements.

Designing a new system is an important creative process. Having abstract requirements help the creative process by not imposing, intentionally or otherwise, a solution to the design. This is particularly true for high-level requirements. The objective is to maximize the design freedom by allowing the evaluation of a large number of alternatives during conceptual design. As the team evaluates concepts and alternatives, it acquires more knowledge about the system. This acquired knowledge enables the team to prevent costly design changes.

The *unique* property implies that there shall be only one requirement per system function. Multiple requirements can be assigned to answer a stakeholder expectation, however each requirement should correspond to a different function of the system. This property is similar to the consistency property, because it is also checking for redundancy and conflicts.

The *complete* property implies that all the information required to understand the stakeholder expectations must be defined during the requirements definition. In other words, a complete requirement should be well-formed by including its related capability, attributes and constraints. This property does not referred to a complete list of requirements for the

entire system. This idea is unrealistic and should be taken more as a goal rather than an achievable objective.

The *achievability* or *feasibility* property relates to the current technical and economical contexts. Regarding the technical context, if the decision makers decide to pursue technologies in order to meet an unrealistic performance requirement, then resources will be allocated to the development of these technologies which, may ultimately not even be used on the system. Regarding the economical context, every project has a fixed amount of available resources. Consequently, the design team must define requirements so that the system reaches the desired level of achievement with the available resources.

All these properties are meant to provide guidelines during the requirements identification and definition phases. The process of defining well-formed requirements based on these properties guide the design teams toward relevant system information.

2.1.3 Definition of System

There are multiple definitions and types of systems. First, this section defines systems based on the INCOSE and IEEE standards. Second, a distinction is made between evolutionary and revolutionary systems. This part also includes a discussion regarding the benefits of a new requirements analysis methodology for revolutionary systems. Third, the concept of revolutionary systems is extended to the concept of Systems-of-Systems (SoS).

The International Council on Systems Engineering defines a system as [83]:

“ a combination of interacting elements organized to achieve one or more stated purposes.”

For example, the wing system shown in Figure 2.2 includes a spar and a flap. Both of these elements are sub-systems, the spar being at the lowest level while the flap is at a higher level because it includes other elements like hydraulics. These elements are interacting together to achieve multiple purposes such as producing lift (wing), sustaining aerodynamics forces (spar) and providing additional lift during landing (flap).

The Institute of Electrical and Electronics Engineers also provides a definition of system [81]:

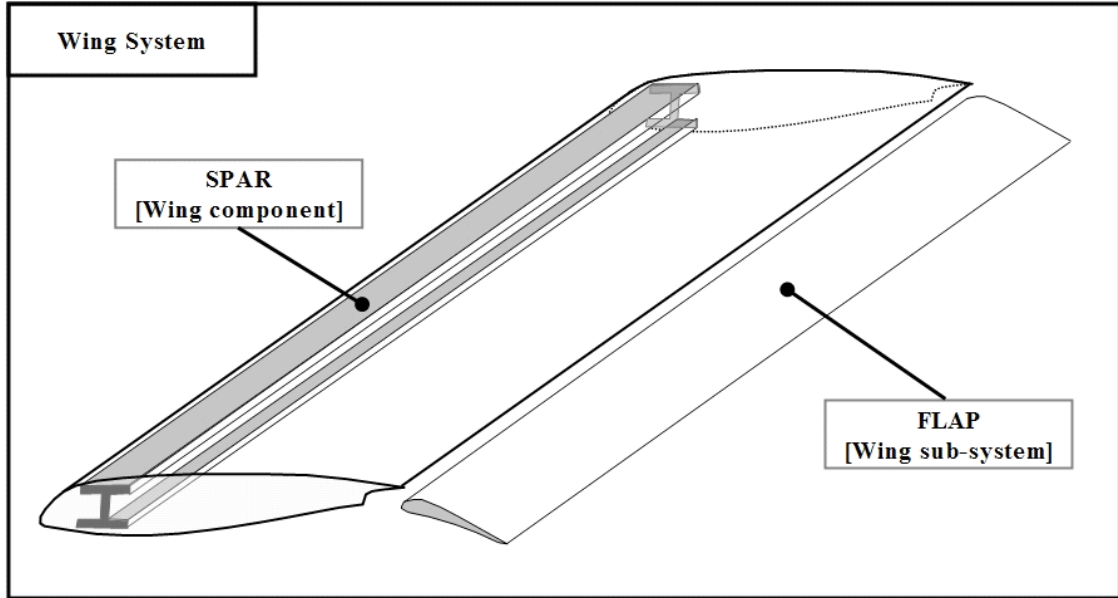


Figure 2.2: Wing system example.

“System: An interdependent group of people, objects, and procedures constituted to achieve defined objectives or some operational role by performing specified functions. A complete system includes all of the associated equipment, facilities, material, computer programs, firmware, technical documentation, services, and personnel required for operations and support to the degree necessary for self-sufficient use in its intended environment.”

This definition states that the system is performing functions, which emphasizes the relationships between systems and requirements since there must be one requirement per function [85]. This definition also provides more information regarding the types of elements included in a system, and it introduces the concept of environment. The concept of environment implies that the system efficiency and performance are functions of the environment. Consequently, it becomes important to also define the environment during the assessment of the customer expectations.

Aerospace engineering includes two general types of systems, evolutionary and revolutionary. Engineers already have experience and knowledge about evolutionary systems, and previous requirements analyses are well documented. Commercial transport airplanes, as

shown in Figure 2.3, are good examples of evolutionary systems, because a large amount of knowledge can be gathered from previous projects. From a requirements point of view, evolutionary systems have similar sets of requirements, which are often based on previous designs. Consequently, the experienced designer is able to rapidly identify important requirements and potential trade-offs. The requirements analysis of a new evolutionary system starts by looking at requirements and trades-offs from historical data, and then apply this knowledge to match functions, requirements and systems to the new project.



Figure 2.3: Evolutionary Design: Commercial Transport Airplanes [3, 20]

On the other hand, the design of a revolutionary system starts with a blank sheet of paper. In this case no historical data is available to rapidly acquire knowledge. The design begins with a list of customer needs, capabilities, requirements, and missions. The level of details provided by the customer varies from system to system. In some cases, customers only have a fuzzy idea of the concept they really want, mainly because the system capabilities have never been fully explored for every potential operational scenario.

Based on the initial customer information and market study, revolutionary systems may involve a large number of requirements, systems, potential shapes and physical configurations. Unmanned Aerial Vehicles presented in Figure 2.4 are good examples of revolutionary systems. Often these systems are not based on previous projects, because they are tailored toward specific applications. At the same time, the engineers have more design freedom with all the number of possible shapes and configurations. Therefore combining less knowledge with more design freedom results in more uncertainty, which increases the difficulty of

matching stakeholders expectations with requirements, systems and resources.



Figure 2.4: Revolutionary Design: Unmanned Aerial Vehicles (NAVY UCAS, Helios, Global Hawk) [2, 137]

It is important to understand that both evolutionary and revolutionary systems can be considered as complex systems. A complex system implies a large number of functions, elements, interactions and therefore a large number of requirements. Complex systems can also be part of systems-of-systems. The International Standards Organization (ISO) formally defines the systems included in SoS [1]:

“are man-made, created and utilized to provide services in defined environments for the benefit of users and other stakeholders. These systems may be configured with one or more of the following: hardware, software, humans, processes (e.g., review process), procedures (e.g., operator instructions), facilities, and naturally occurring entities (e.g., water, organisms, minerals). In practice, they are thought of as products or services. The perception and definition of a particular system, its architecture and its system elements depend on an observer’s interests and responsibilities. One person’s system of- interest can be viewed as a system element in another person’s system of- interest. Conversely, it can be viewed as being part of the environment of operation for another person’s system-of-interest.”

This definition adds to the other system definitions by including the stakeholder’s perspective. Systems-of-systems involve multiple layers of systems, and at each of these layers there are stakeholders responsible for individual systems. Figure 2.5 presents a UAV systems-of-systems example with multiple layers of elements. There are three main systems: UAV,

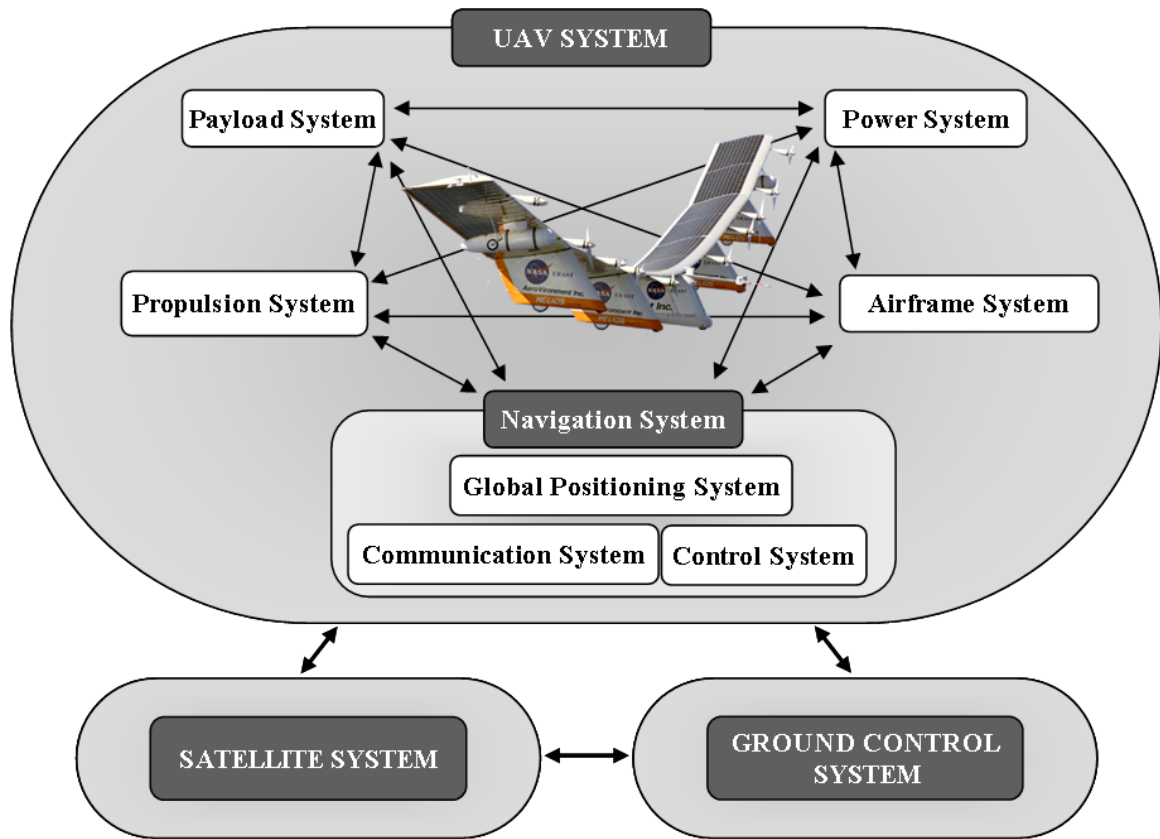


Figure 2.5: UAV systems-of-systems example.

ground control and satellite. The UAV system is expanded into multiple lower level systems including the navigation system, which is expanded into sub-systems. The arrows between the systems imply that some elements of one system are impacting elements of the other system. Assuming that a single system, like the propulsion system, includes a relatively large number of requirements, one can easily imagine how fast the number of requirements is growing by combining all the other system's requirements. Related to the design of systems-of-systems, the INCOSE handbook identifies seven challenges listed as follows[83]:

1. System elements operate independently;
2. System elements have different life cycles;
3. **The initial requirements are likely to be ambiguous;**
4. **Complexity is a major issue;**
5. **Management can overshadow engineering;**
6. **Fuzzy boundaries cause confusion;**

Table 2.2: Life cycle stages. Source INCOSE [83].

Life Cycle Stages	Purpose
CONCEPT	Identify stakeholder's needs Explore concepts Propose viable solutions
DEVELOPMENT	Refine system requirements Create solution description Build system Verify and validate system
PRODUCTION	Produce systems Inspect and test (verify)
UTILIZATION	Operate system to satisfy user's needs
SUPPORT	Provide sustained system capability
RETIREMENT	Store, archive, or dispose of the system

7. SoS engineering is never finished.

Five of these challenges (bold) are part of this research scope. The proposed methodology is meant to reduce the ambiguity and help the management to better understand the problem by providing more information and knowledge to decision makers and engineers. The fuzzy boundaries might still be present, but tools and processes can be used to provide qualitative and/or quantitative assessment of these boundaries. Finally, assuming that SoS are very likely to change, the proposed methodology could easily be modified to assess changes of stakeholders expectations or capabilities due to the evolution of social-economics environments.

2.2 Introduction to the System Life Cycle

The system life cycle includes all the activities from market and customer analyses to the disposal of the system. Understanding the system life cycle emphasizes the interactions and importance of requirements in a project. Also, looking at the big picture helps to identify the information needed to start the requirements process, and how the outcomes of the requirements process are used in the later stages of the life cycle. Table 2.2 depicts the different stages of the system life cycle with their respective purpose.

Even though the proposed methodology is applied during the concept stage, its impact can go as far as the retirement of the system. For instance, if one requirement leads to the

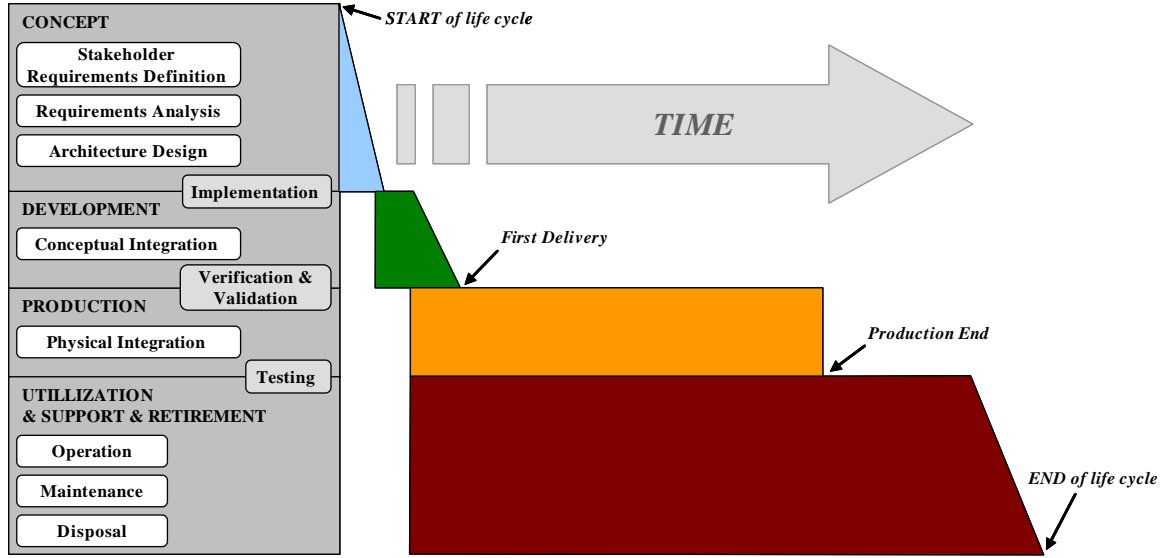


Figure 2.6: Systems life cycle processes. Inspired from [83].

selection of a specific material, then this choice has a great impact on how the system is disposed at the end of its life.

There are specific systems engineering processes associated with the different stages of the life cycle as illustrated in Figure 2.6. Some of these processes enable a smooth transition between the different stages. This figure also shows a relative time line of each stage. The concept and development phases are relatively short compared to the production and utilization phases, however they greatly impact the outcome of the project. For instance depending on the product success the operation can be short lived like the B-70 supersonic bomber which was canceled before the production started. On the other hand, if the product is successful then its utilization can be very long which is the case of the B-52 bomber, in operation since 1952.

Each process has an impact on the next one, consequently the first few processes of the life cycle are critical to the success of the new product. The requirement analysis methodology at the beginning of the life cycle has a great impact on the entire system development. The process preceding the requirements analysis is the definition of stakeholder's expectations. This process is also part of this thesis scope, and its purpose is to match stakeholders expectations to requirements. The process following the requirements analysis is the analysis

of alternatives. The objective of the analysis of alternatives is to establish a combination of systems solutions that have the potential of meeting the stakeholders expectations and requirements. The identification of the systems solutions is necessary to provide a connection between the stakeholders, requirements and systems.

The big picture of the system life cycle helps to frame the role of requirements in the conceptual design process. The design wheel, presented in Figure 2.7, is a simplified design process illustrating relationships between requirements, design concepts (systems solutions), design analysis, and vehicle sizing. Design analysis includes disciplinary analysis such as aerodynamics, propulsion and mission analysis, while the vehicle sizing includes performance and economics trade studies. The design wheel shows two iteration loops, one between the requirements and the vehicle sizing, and the other between the design concept, design analysis and the vehicle sizing. Information acquired during the vehicle sizing and trade-studies is reused to validate the requirements and to improve the design concept.

The next section describes established requirements analysis processes being part of more complex conceptual design methodologies.

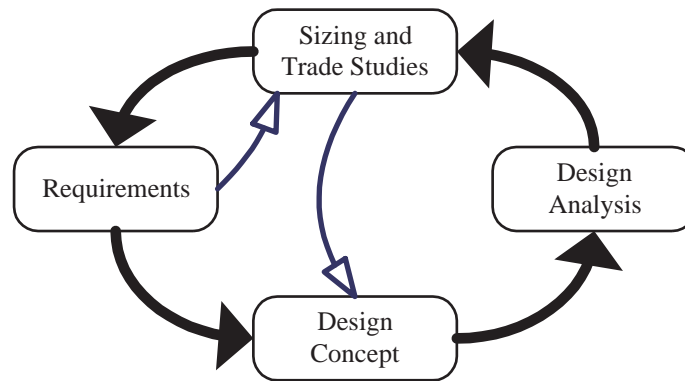


Figure 2.7: The Design Wheel [145]

2.3 Review of Current Requirement Analysis Processes

Up to this point, this research scope has been explored by defining important terminology. This section reviews current requirements analysis processes used in academia and industry.

The top-level goals of a requirements process is to identify, define (model) and select a set of requirements that drives the design of the system. In the context of a complex system life cycle design, this section describes the INCOSE, DoD and NASA requirement analysis methodologies while inferring relationships with this thesis research's areas.

2.3.1 Introduction to the Requirement Analysis

“... the ability to define the problem is the most important and difficult task in engineering”.

-Nam P. Suh, *The Principles of Design* [165]

The requirement analysis process is at the front line of the system's problem definition. This section introduces the general activities performed during requirements analysis. The description of these activities is important to understand the requirements methodologies discussed in the remaining section.

The requirements process starts with the stakeholders or end-users (1) expectations as shown in Figure 2.8. The design team has to gather relevant information within the problem domain (1) to acquire additional system knowledge. Subsequently this knowledge is used in the three main activities of the requirements methodology: requirements elicitation (2), requirements specification (3), and requirements validation (4).

The objective of the elicitation activity is to identify any requirements related information. During this stage, engineers define the problem starting with stakeholders needs. The goal of this step is to gain a better understanding of the customer expectations. Once the needs and expectations are defined, the design team can list potential requirements needed to achieve the system's functions. These requirements can then be classified into subsets. The classification process may differ depending on the project or even depending on the interpretation of the requirements by the design team.

The knowledge acquired during the elicitation step is transferred to the requirements specification activity which defines requirements according to the properties described in

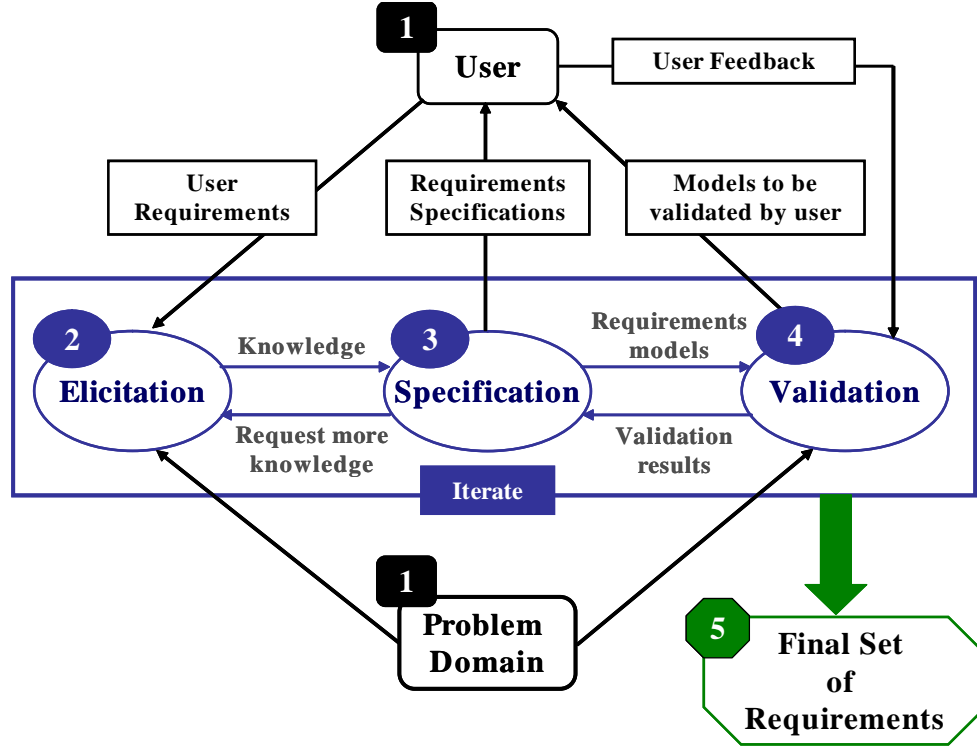


Figure 2.8: Framework for requirement engineering process. Modified from [107])

section 2.1.2.1. The specification process translates qualitative requirements from stakeholders into measurable quantitative engineering characteristics. Once requirements are modeled, the validation activity sorts through all the requirements and defines their importance. Due to the large number of requirements and fixed amount of resources, it is practically impossible to satisfy all requirements. Consequently, trade-offs needs to be made between the important requirements and the available resources.

Requirements analysis is an iterative process as shown in Figure 2.8. As the design team gains knowledge about the systems, new requirements are identified which also require specification and validation. The main outcome of the requirements analysis process is a set of requirements (5) that matches the stakeholders expectations, and is feasible from a cost and schedule perspective. The final set of requirements should be balanced between performance, cost and schedule in order to drive the system design through its next life cycle stage. At this project milestone, a document including a detailed description of the requirements is created and distributed to stakeholders. This document may be incorporated

into a contract that binds stakeholders during the system’s design.

2.3.2 INCOSE Requirements Methodology

This thesis revolves around the conceptual stages of the design life cycle. The International Council in Systems Engineering identifies three major processes related to conceptual design: *stakeholder requirements definition*, *requirements analysis* and *architectural design* [83]. This section describes these processes in relationship with the scope of this thesis, and more specifically the following research areas: requirements mapping, uncertainty analysis, resource allocation and requirements selection.

The stakeholder requirements definition process corresponds to the elicitation activity (Figure 2.8) that must be performed in requirements analysis. This process objective is to match the stakeholder’s expectations with requirements. The design activities of this process are based on inputs, enablers and controls conditions as illustrated in Figure 2.9. The inputs

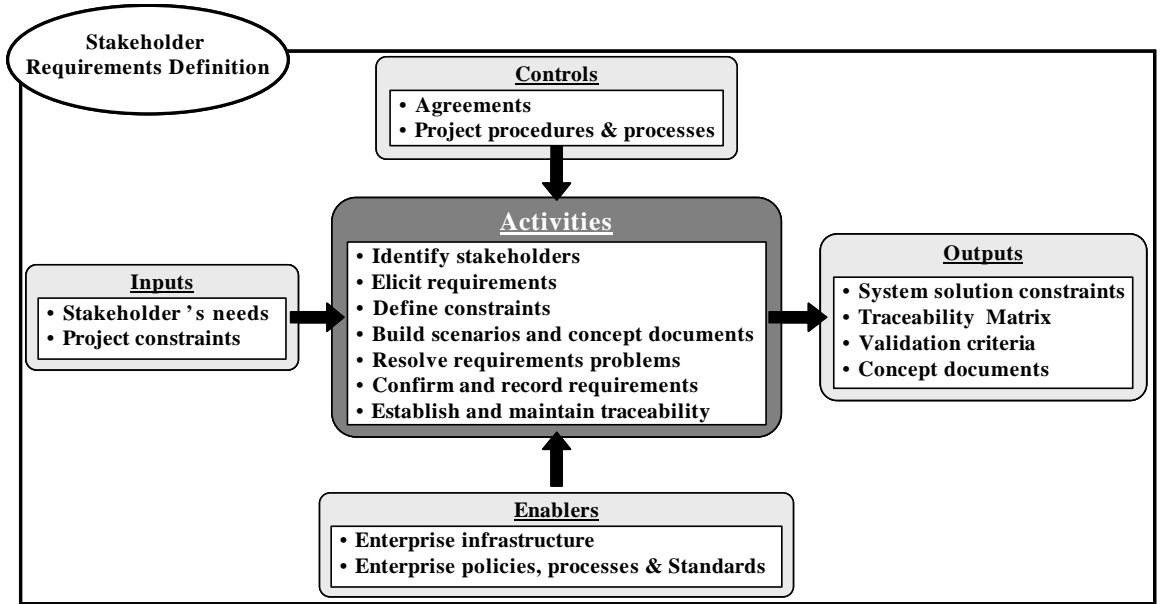


Figure 2.9: INCOSE: Stakeholder requirements definition process. Source [83].

are generally stakeholder’s needs, project constraints and resources. The control conditions and enablers bound the project in the enterprise, industrial and market contexts. The main activities of the process are performed by the design team to trace together stakeholders, requirements and appropriate validation criteria defining the customer satisfaction.

Table 2.3 depicts how the stakeholder requirements definition process is related to this thesis’s research areas. Since the INCOSE handbook is intended to be general and applicable to a large number of systems, there are no specific tools and techniques identified to reach the desired outputs. One of the intents of this thesis’s proposed methodology is to identify specific tools and techniques to achieve these outcomes for complex aerospace vehicles. The outputs of the stakeholder requirements definition become inputs to the INCOSE requirements analysis process as shown in Figure 2.10.

Table 2.3: Research areas vs. stakeholders requirements definition

Research	Advantage	Shortcoming
Requirement mapping	Traceability between stakeholders and requirements	No technique specified
Resource allocation	Define project constraints	No technique specified
Uncertainty analysis	Ambiguity reduced by defining scenarios and traceability	No technique specified
Requirements selection	Establish a set of validation criteria	No decision making tool specified

The purpose of the INCOSE requirements analysis activities is to further define the requirements by establishing functional and performance objectives. Also, the traceability of requirements is extended to the systems by identifying architectural constraints. An architecture is defined as the synthesis of systems solutions to create one whole system. The goal is not to define the exact systems solution, but to try to identify potential requirements derived from the synthesis of multiple systems. These activities can lead to additional verification criteria in terms of Measures Of Performance (MOP) and systems Measures Of Effectiveness (MOE) to validate the final customer satisfaction. The relationship between the INCOSE requirements analysis process and the research areas are relatively the same as the ones presented in Table 2.3, however there is one additional challenge concerning the requirement mapping.

This mapping challenge is caused by the type of information used in the requirements methodology. There are two types of information, qualitative and quantitative. The main challenge comes from the transition between qualitative and quantitative information. On

one hand, stakeholder requirement definitions are based on qualitative information. On the other hand, the construction of the systems architecture requires quantitative information needed to define performance requirements and architectural constraints. Consequently, there needs to be an activity ensuring that all the relevant qualitative information are translated into quantitative information. For instance, if the stakeholders want the system to be “safe”, then the design team needs to define how to quantify the desired “safety” attribute.

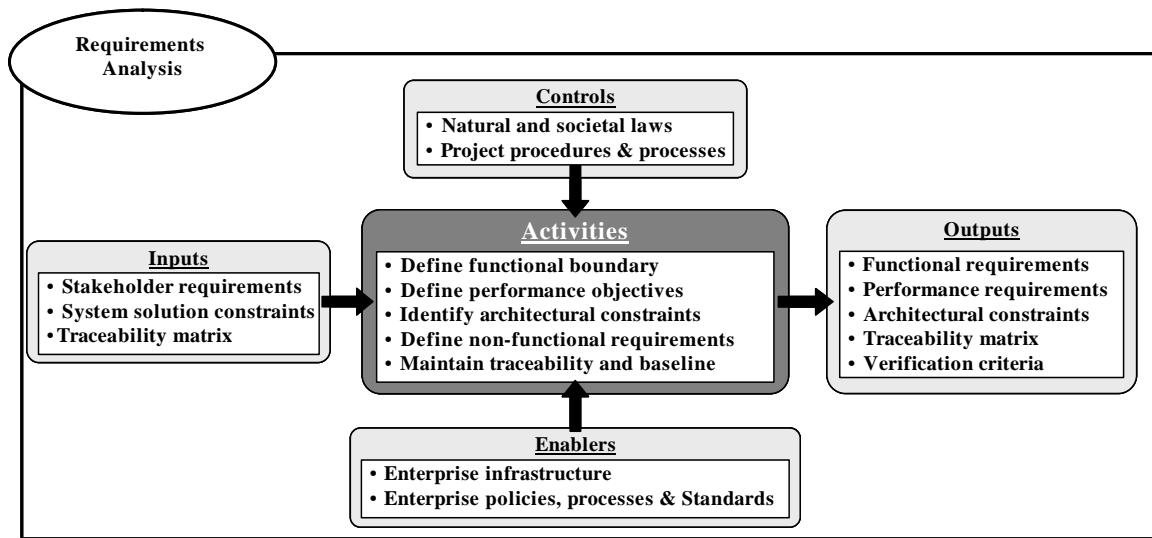


Figure 2.10: INCOSE: requirements analysis process. Source [83].

From the requirements analysis process, Figure 2.10, a large number of system solutions can be identified to meet the stakeholders functional and performance requirements. The purpose of the INCOSE architecture design process is to sort through the previously gathered information and select a baseline system. The activities required to achieve this goal are shown in Figure 2.11. The first activity is to define the logical architecture able to perform all the stakeholder desired capabilities. The term logical refers to the structural decomposition of multiple levels of requirements and functions. For instance the function “*lift weight*” can be associated with the wing system, while the function “*sustain aerodynamics forces*” can be associated with the wing structure or more specifically the wing spar. The traceability between the different levels of functions, requirements and systems is essential to assess the impact of requirement changes on the systems and on the customer satisfaction.

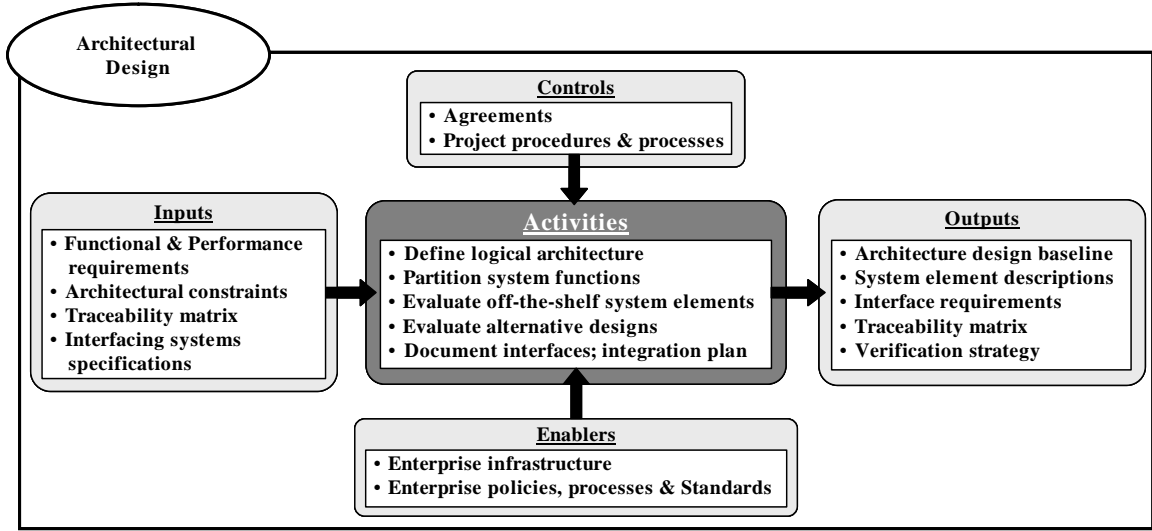


Figure 2.11: INCOSE: Architectural Design. Source [83].

Once the logical architecture completed, it is important to evaluate design alternatives by exploring which combinations of systems are best suited to meet the requirements. This activity can be done qualitatively or quantitatively depending on the available information. A qualitative analysis requires expert judgment to compare alternative solutions. A quantitative analysis implies the use of modeling and simulation tools created from historical databases or from physics-based models. These tools are used to evaluate the system alternative capabilities. Furthermore, the modeling and simulation tools can also be used as a verification strategy for requirements.

As mentioned earlier, the objective of the proposed methodology is not to select a baseline system architecture, but to down-select the number of requirements. The architectural design process includes relevant systems information that can be very useful during the requirements down-selection process. It is assumed by the author that a thorough requirements analysis must include at the very least a general systems architecture, and the enumeration of potential system solutions.

2.3.2.1 Relationships between the INCOSE process and research scope

The INCOSE requirements analysis methodology is an iterative process including three technical processes: stakeholder requirements definition, requirements analysis and architectural

design. The purpose of the INCOSE methodology is to provide a general set of activities required to define a solid starting point for the project. In this research, a solid starting point corresponds to the selection of a set of requirements that will drive the life cycle design.

The main INCOSE activities consist of assuring requirements traceability, establishing measures of effectiveness, measures of performance, and defining validation criteria for the system. With respect to the scope, these activities need to be related to the research areas of requirements mapping, uncertainty analysis, requirements down-selection and resource allocation.

The traceability between stakeholders, requirements and systems is embedded in the requirements mapping. The main challenge of this activity is to translate qualitative (subjective) information into quantitative information that can be measured on the system. The traceability property also tends to reduce the process uncertainty, however there are no activities specifically tailored to analyze the uncertainty related to the stakeholder's expectations, requirements definition and systems characteristics.

The INCOSE activities of defining MoEs, MoPs and validation criteria can be associated to the requirements down-selection and resource allocation respectively; however some MoE and MoP could also be used as validation criteria. All of the INCOSE activities are deemed important in this thesis scope. Much effort is made in the proposed methodology to associate these activities with a set techniques and tools allowing a better understanding of the requirements analysis process.

2.3.3 DoD Requirements Methodology

The Department of Defense also defines a requirements analysis methodology in their *Systems Engineering Fundamentals* handbook [43]. The DoD Systems Engineering Process (SEP), including the requirements analysis, is shown in Figure 2.12. There are obvious similarities between the DoD SEP and the INCOSE process. Both processes have a requirements analysis process with the goal of defining functional and performance requirements. Also, they both have a systems architecture synthesis stage which consists of analyzing different systems solutions and combining them together in order to find the best architecture that

satisfies the stakeholders expectations.

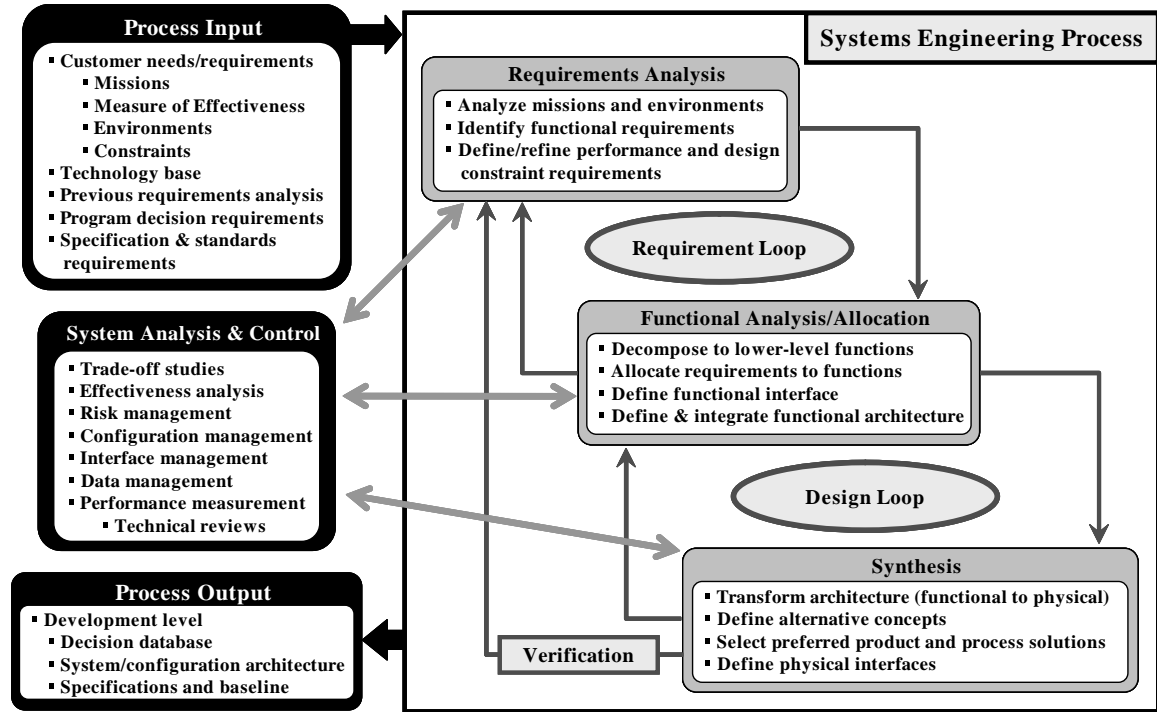


Figure 2.12: DoD: Systems engineering process. Modified from [43].

The methodologies also have some key differences. On one hand, the DoD SEP has been developed in the context of systems acquisition; it is used in a contractual context, consequently it assumes an initial set of customer requirements. On the other hand, the INCOSE framework assumes that the initial set of requirements comes from a collaboration between the stakeholders and design team. Another difference is the interim functional analysis/allocation process of the DoD framework. This interim step is embedded in the INCOSE requirements analysis process. The advantage of having this interim step is to visualize and better understand the requirements interactions in the requirement and design loops. The requirement loop is necessary because every requirement needs to be traced to a function; while the design loop implies that every function needs to be performed by one or multiple systems. The DoD process also includes a verification loop evaluating how the system architecture meets the initial requirements. In the acquisition context, this verification is essential to assure the prolongation of the contract.

An interesting feature of the DoD process is the integration of system analysis and control

management techniques. These activities are related to the three main systems processes, and their main goal is to manage the large amount of information created as the problem evolves. The outputs of the DoD process include a decision database from trade-off studies, a system architecture and requirements specifications. If the stakeholders are satisfied by these outputs, then the project enters the preliminary design stage.

2.3.3.1 Relationship between DoD process and research scope

The Department of Defense requirements analysis methodology is based on a contractual context. This characteristic does not diminish in any way its applicability to complex systems design. The DoD process could simply be extended by adding a “*stakeholder loop*” before the requirement loop. This iteration would enable the matching of the stakeholder expectations with the functional requirements of the requirement analysis process. The remainder of this section describes the relationships between the DoD process with the thesis scope: requirements mapping, resource allocation, uncertainty analysis and requirements down-selection.

The requirements mapping with the stakeholders and systems is assured by defining a functional architecture. This functional architecture is a result of the function analysis assuring the continuity of information between requirements and systems analyses. In the DoD process, the mapping between requirements and resources needs to be improved. This mapping has a great impact on cost growth and schedule delay. For instance, Figure 2.13 shows the significant cost growth of complex weapons systems. The schedule delays result in cost growth, and to compensate the additional investment there is generally a reduction of the initial production quantity. The evaluation of the committed cost is part of the resource allocation process. Due to the contractual nature of the DoD process, the resources-stakeholder expectations mapping needs to be improved by defining new activities and management processes.

The DoD process include some activities that tend to reduce the uncertainty. The classification of functions and systems in architectures helps to decompose the problem complexity while reducing the ambiguity. Also the system analysis and control techniques structure

Program		Initial estimate	Initial quantity	Latest estimate	Latest quantity	Percentage of unit cost increase
Joint Strike Fighter		\$196.5 billion	2,866 aircraft	\$223.3 billion	2,458 aircraft	32.8
Future Combat Systems		\$85.5 billion	15 systems	\$131.7 billion	15 systems	54.1
V-22 Joint Services Advanced Vertical Lift Aircraft		\$36.9 billion	913 aircraft	\$50.0 billion	458 aircraft	170.2
Evolved Expendable Launch Vehicle		\$16.0 billion	181 vehicles	\$28.6 billion	138 vehicles	134.7
Space Based Infrared System High		\$4.2 billion	5 satellites	\$10.4 billion	3 satellites	311.6
Expeditionary Fighting Vehicle		\$8.4 billion	1,025 vehicles	\$11.3 billion	1,025 vehicles	33.7

Source: GAO analysis of DOD data. Images sourced in their respective order: JSF Program Office; Program Manager, Future Combat Systems (BCT); V-22 Joint Program Office; (Left) © 2005 IL/Lockheed Martin, (right) © 2003 The Boeing Company; Lockheed Martin Space Systems Company; General Dynamics Land Systems.

Figure 2.13: Complex weapon systems cost growth. Source [182].

and manage the massive amount of information for the decision makers. An additional control technique translating the qualitative information into quantitative measures based on specific assumptions would also help to improve the uncertainty analysis.

The DoD process does not specify how the requirements down-selection is performed. Is it based on the systems analyses? If the answer is yes, how to integrate the results of trade studies, effectiveness and risk analyses to down-select of requirements? The current process does not specifically discuss these important characteristics of the requirements analysis process.

2.3.4 NASA Requirements Methodology

NASA recently released a new procedural requirements document entitled “*Systems Engineering Processes and Requirements*” [131]. The main objective of this document is to define processes to support, perform and evaluate systems engineering activities. The flow of processes, illustrated in Figure 2.14, include nine design (1-9) and seven management processes

(10-17).

The initial design processes (1-4) decompose the complexity of the problem starting from general to specific concept (Top-Down approach). The knowledge acquired during the definition activities is going into management processes (10-17). The information stored is then used as input for the realization of the product (5-9), starting from individual systems to the integrated final systems (Bottom-Up approach). The pyramid of systems (Work Breakdown Structure, WBS), at the bottom of Figure 2.14, illustrates the fact that multiple lower level systems (bottom) are required to achieve the final complex system (top) . Also, the original figure has been modified to show the design processes included in this thesis scope, they are: (1) stakeholder expectations definition, (2) technical requirements definition, (3) logical decomposition, and part of (4) design solution definition. The management processes are also included in order to store the information gathered while executing the design activities.

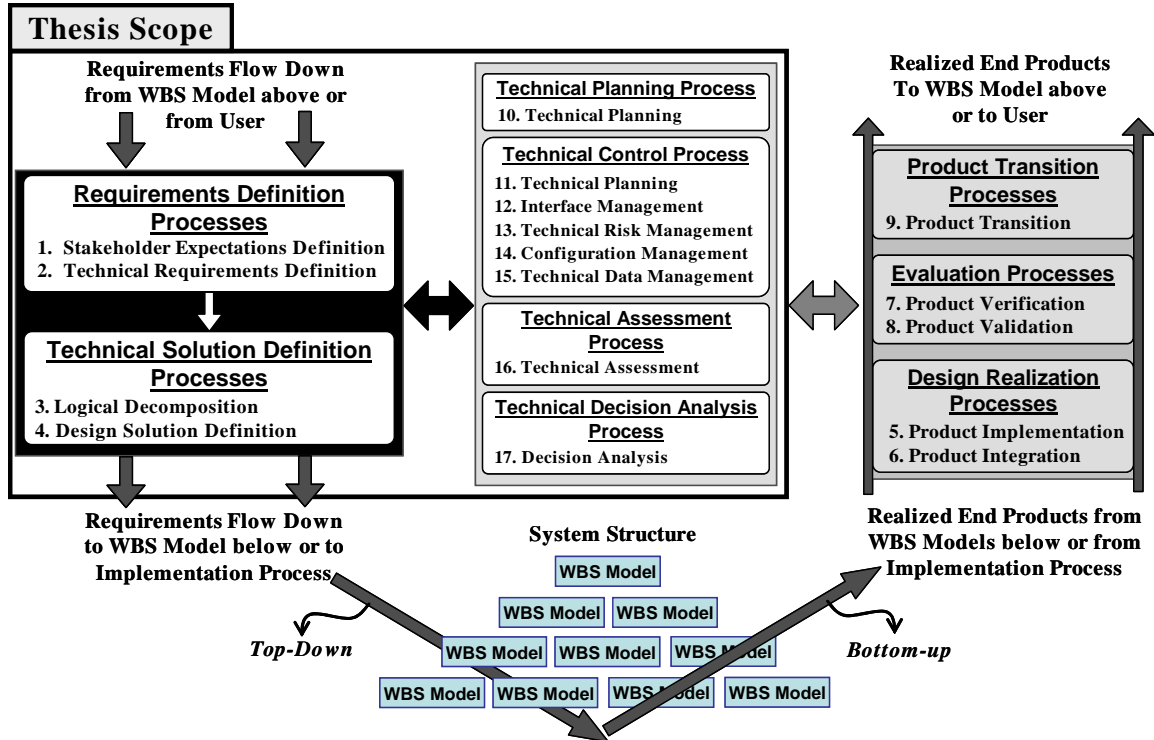


Figure 2.14: NASA: Systems engineering processes. Modified from [131].

The NASA process starts with the analysis of stakeholders expectations. The initial

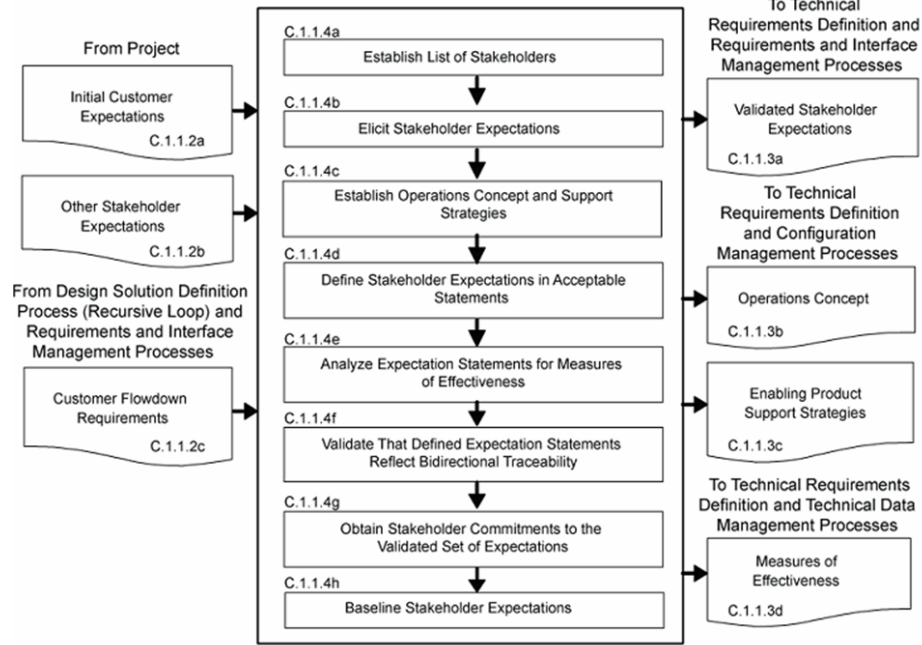


Figure 2.15: NASA: Stakeholder expectations definition process. Source [131].

expectations are coming from many different stakeholders; they are generally based on operational missions, desired capabilities, standards, regulations and system life cycle constraints. This process consists of eight design activities intended to reduce the uncertainty surrounding the initial expectations, as shown in Figure 2.15. The main goal of these activities is to validate the stakeholder expectations by establishing clear definition and verifiable MoEs. Examples of MoEs are weight, survivability, modularity and availability. In order to reduce the ambiguity, it is suggested that the expectation definitions should be a simple statement as “*actor-verb-object*”[131]. The outcomes of this process are passed to the relevant management processes and to the technical requirements definition process.

The second process establishes the technical requirements definition. This process transforms the stakeholder expectations from qualitative statements to quantitative and measurable requirements. The first activity consists of defining the problem scope by analyzing the desired system functions and constraints. The functions and constraints may either come from the stakeholders or the environments, and be under the control of the design team or not. Each function must be related to at least one performance characteristic, for example the function “*transport payload*” implies payload weight as performance characteristic. The

next step is to formalize constraints, functions, performance characteristics into technical requirements.

Using the same example, a formal technical requirement would be: “*the aircraft shall transport 200 lb of payload at cruise altitude, while being able to maintain a rate of climb greater than 300 ft/min*”. In this case the altitude would represent the constraint. The technical requirement has to be validated by defining its assumptions and demonstrating the traceability with the stakeholders. If a technical requirement is still qualitative, such as the “*aircraft seat shall be comfortable*”, some measure of performance are needed to define the concept of “*comfort*”. One of the last activities of the requirements definition process is to define Technical Performance Measures (TPM). The TPMs are often the most important MOPs; they represent warning criteria for the design team and decision makers during a design review.

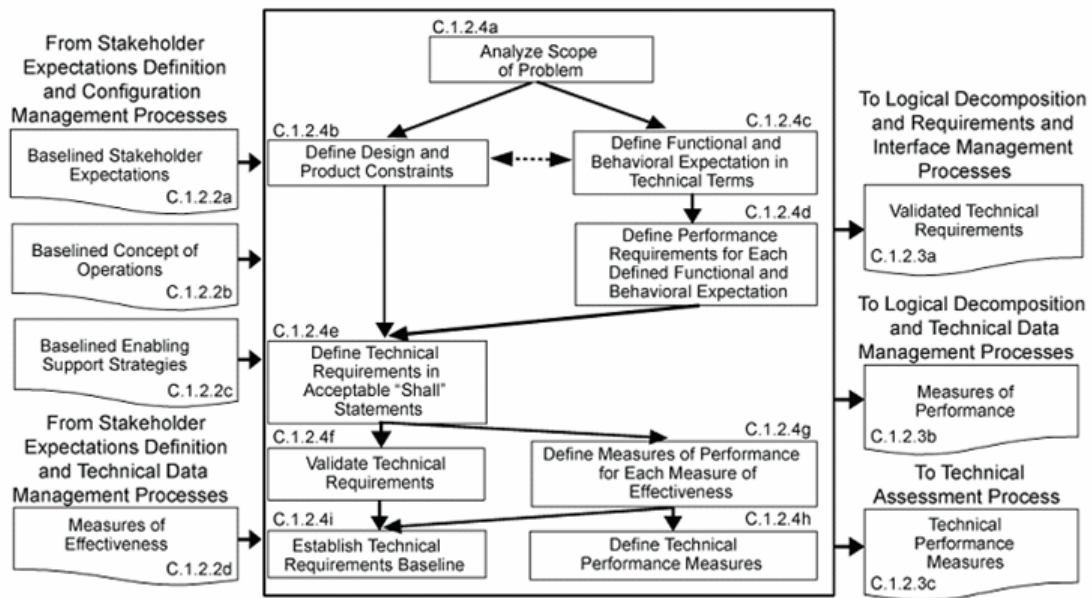


Figure 2.16: NASA: Technical requirements definition process. Source [131].

The design of a complex system involving many expectations, functions and constraints implies the definition of a large number of requirements. The logical decomposition process, shown in Figure 2.17, has for objective to structure the previously gather information by defining relationships between requirements and systems (models). A Top-Down approach

is used to decompose the complex system into multiple levels of systems. Each individual system has to perform a series of functions, and the technical requirements are allocated to the systems based on the requirement-function relationships. It is to be noted that a technology can also be viewed as a system, therefore new technologies also need to be associated with functions, systems and technical requirements.

When all requirements are associated to their respective systems, the logical decomposition needs to be analyzed to identify conflicting requirements. The analysis is done based on performance criteria and systems available resources (i.e., cost, risk, schedule). This activity involves important trade-offs that are taken into account before the selection of the system baseline configuration. It is also essential to document these trade-offs with their associated assumptions and decision rational to provide an understanding of the conflicts. Using the trade-offs information, the last activity of the logical decomposition process is to down-select the number of requirements into a manageable number. This set of requirements is called the derived technical requirements baseline. These requirements are the basis for the Analysis of Alternatives (AoA).

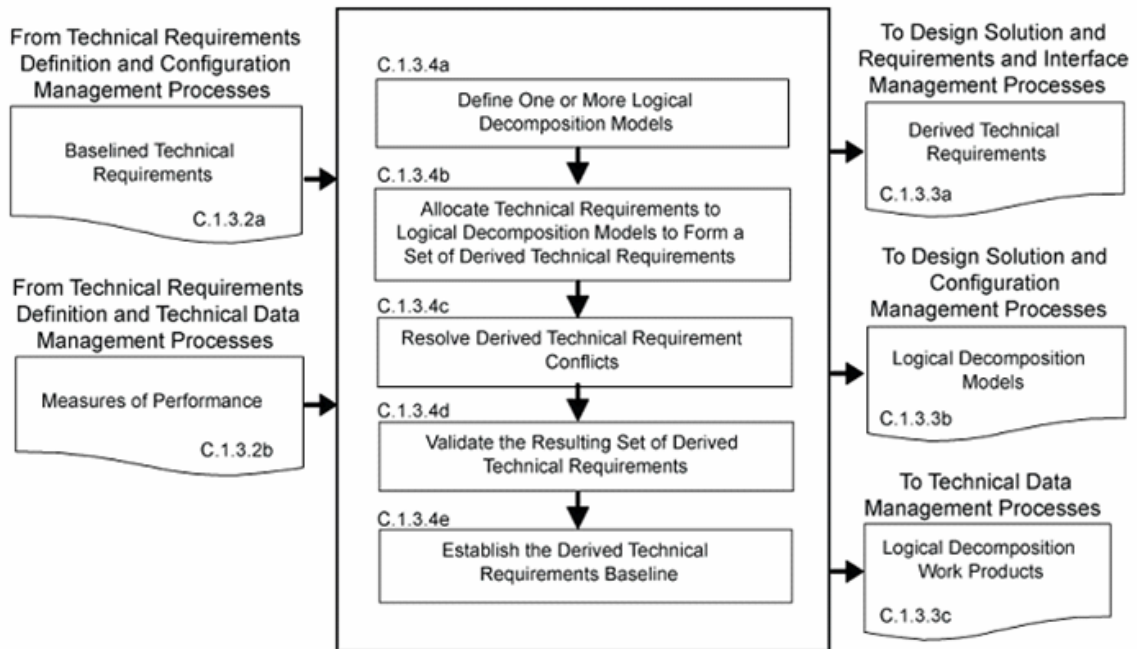


Figure 2.17: NASA: Logical decomposition process. Source [131].

The design solution definition consists of creating combinations of systems alternatives “to build” the whole complex systems. The process is illustrated in Figure 2.18. During the logical decomposition only the abstract systems, like “wing” and “engine”, are taken into account. In the design solution definition, each of these abstract systems are extended into alternative solutions. For instance, the engine system could have the following alternative solutions: internal combustion, turbojet, turboprop or turbofan. The baseline solution of the complex system is created by selecting one alternative solution for every system. Once a combination is completed, the design team analyzes the integrated system. This analysis enables the verification of the derived technical requirements and stakeholder expectations. This activity is usually executed with an appropriate modeling and simulation environment. The outcome of this design analysis leads to the selection of the baseline system configuration.

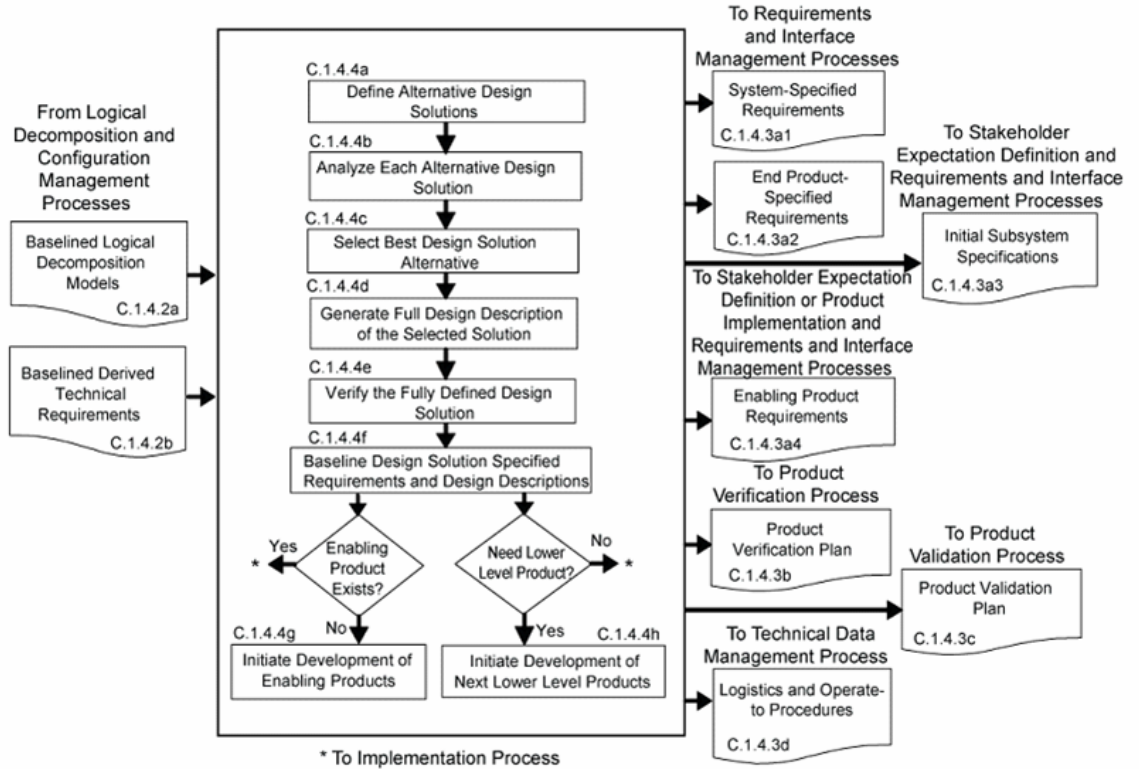


Figure 2.18: NASA: Design solution definition process. Source [131].

The selection of the baseline system configuration is outside of this thesis scope, however some activities of the design solution process could be used for requirements mapping,

resource allocation and requirements down-selection. For instance, physics-based models within the modeling and simulation environment can be used to refine the relationships between performance requirements and systems characteristics. This statement will be further described during the description of the proposed methodology.

2.3.4.1 Relationship between NASA process and research scope

The NASA requirements methodology provides a structured framework to identify, define and select requirements during the system conceptual design. This section describes relationships between this thesis research areas and several design activities mentioned in section 2.3.4.

Regarding the requirements mapping, it is emphasized in the NASA document to have bidirectional traceability between stakeholders expectations, technical requirements and WBS models (systems). These relationships are stored and documented in the requirements management process. Furthermore, the logical decomposition of the complex system provides guidelines to better understand and define relationships between the technical requirements and the system models. The system structure allows the visualization of the requirement-system mapping, which also helps to enhance the stakeholders understanding of the problem while reducing interactions ambiguity.

Complex interactions and relationships between requirements and systems also tend to create uncertainty. The uncertainty in the NASA requirements methodology is taken into account by eliciting the stakeholder's expectations, analyzing the problem scope, establishing measures of effectiveness and performance, and by defining requirements with an "acceptable *shall* statement"[131]. The uncertainty can also be captured by documenting assumptions, decision rationale and managing the mass of information gathered during the process. However, there are different types of uncertainty that require different mitigation techniques, which underline the need for the addition of an uncertainty management process. This possibility will be explored in the proposed methodology.

The management processes also provide valuable inputs to the requirements definition. For instance, the initial evaluation of the project's required resources is conducted within

the technical planning process. This activity starts the resource allocation by estimating project cost and schedule. More resources related information is defined by establishing product constraints during the technical requirements definition process. These resources are then formally included in the technical requirement definitions. Assuming a large number of technical requirements, each with associated resources, trade-off studies are required to analyze the number of requirements that can be satisfied within the fixed amount of available resources. Consequently, the problem is to allocate the resources while trying to maximize the stakeholder satisfaction. This problematic leads to the requirements down-selection research area.

In addition of the required resources, measures of effectiveness and performance can also be used as criteria for trade-off analyses and requirements down-selection. In the NASA requirements methodology, the derived technical requirements baseline is established at the end of the logical decomposition process. The methodology does not clearly specify if all the technical requirements are included in the baseline or if the requirements down-selection is performed during the design solution definition process. These aspects of the problem will also be taken into account in the proposed methodology.

Currently, the NASA Systems Engineering Handbook, written in 1995 [132], is not taking into account the new processes described in the NASA Systems Engineering Processes and Requirements document. According to ref. [131], NASA plans to update the systems engineering handbook by adding methods addressing the new processes. One of the objectives of this research is to build on current methods in order to address the previously described processes while focusing on requirements mapping (traceability), uncertainty analysis, resource allocation and requirements down-selection.






















2.4 Summary of Requirements Methodology

The General Accounting Office emphasizes that a successful project starts by matching stakeholders expectations with requirements and resources [180, 181]. As the systems are getting more complex, more information is required for the matching of expectations and requirements. Therefore, requirements methodologies are trying to capture the systems

complexity by dividing and structuring complex relationships into manageable problems. By doing so, it reduces the ambiguity surrounding the problem definition and provides a solid starting point for the design process.

The previous section reviewed current requirements analysis methodologies used in the industry. In relationship with this thesis scope, several key requirements methodology characteristics are used for comparison:

- Qualitative/Quantitative transition: Provide a continuous flow of information by translating qualitative information into quantitative measures. This characteristic is particularly important for the modeling of subjective requirements.
- Structured framework: Regroup and classify concepts to understand the flow of information from the stakeholder's analysis to the requirements down-selection. The framework implies the iteration loop between the processes and the management technique used to manage and store the information.
- Requirements mapping: Define the continuous mapping of information between stakeholders, functions, requirements and systems. This characteristic includes the bidirectional traceability between these concepts.
- Resource allocation: Define the initial resources available and techniques to allocate them to requirements. The resource allocation helps to determine a relative committed cost value per requirement.
- Uncertainty analysis: Assess the uncertainty surrounding the stakeholder expectations, requirements and systems characteristics. The management of uncertainty starts by defining the type of uncertainty and approaches to mitigate or capture the ambiguity.
- Requirements down-selection: Establish a set of criteria to down-select the number of requirements. These criteria should be based on the importance of stakeholders and functions, and the impact of the requirements on the stakeholders, functions, requirements and systems.

	INCOSE	DoD	NASA
Qualitative/Quantitative transition			
Structured framework			
Stakeholders Analysis			
Requirements mapping			
Resource allocation			
Uncertainty analysis			
Requirements down-selection			






 **Excellent**
 **Very Good**
 **Good**
 **Fair**
 **Poor**

Figure 2.19: Qualitative comparison of requirements methodologies.

A qualitative comparison of the requirements methodologies, based on these key characteristics, is presented in Figure 2.19.

On one hand, this figure indicates that the three methodologies are relatively good with respect to the requirements characteristics. They are providing a structured framework to guide engineers and decision makers through the processes. Also, the methods strongly emphasize the stakeholder analysis and requirements mapping. On the other hand, the comparison reveals some shortcomings regarding the resource allocation, uncertainty analysis and requirements down-selection processes. Based on these limitations, several questions are needed to clarify the potential methods used in the requirements methodology. These questions are enumerated as follows:

1. How to assure bidirectional traceability through requirements mapping?
 - i. How to map stakeholders, functions, requirements and systems to track design changes?
 - ii. How to classify the stakeholders, functions, requirements and systems according to a specific mapping?
2. How to assess the requirements related uncertainty?
 - i. How to classify uncertainty?
 - ii. How to manage uncertainty?
 - iii. How to include the uncertainty within the requirements mapping?

- iv. How to model subjective requirements?
- 3. How to allocate resources under uncertainty?
 - i. What are the available resources?
 - ii. How to allocate intangible resources such as risk, safety, etc?
- 4. How to perform the requirements down-selection?
 - i. What are the important evaluation criteria?
 - ii. How many requirements can one satisfy with the available resources?
 - iii. Does the system alternative choices have an impact on the requirements down-selection process?

These questions are listed here to guide the literature review, and create a foundation for a preliminary methodology. With the new information gathered during the literature reviews and some experimentation, these questions will later be formalized as research questions. The next chapter is a literature review of methods and tools that are associated with the main research areas of this thesis.

2.5 Building a Methodology

From the information gathered in this chapter, the relationships between this thesis research and the current requirements methodologies are leading toward the development of the proposed methodology. A simplified version of the proposed requirements methodology is illustrated in Figure 2.20. This figure shows the interactions between goals, important results and examples of processes and tools. The first goal consists of defining how to satisfy the stakeholders expectations. This model shall include a definition of stakeholder expectations, associated functions and formalized requirements statements. The second goal consists of defining how to satisfy the requirements statements. Reaching this goal requires the identification and definition of systems characteristics and alternatives. Processes and tools are used to obtain these critical results, and they are also used to manage the information and knowledge resulting from every step of the methodology.

With respect to the observations and research questions emerging from the scope definition, Figure 2.21 illustrates the flow between the observations, the research questions and

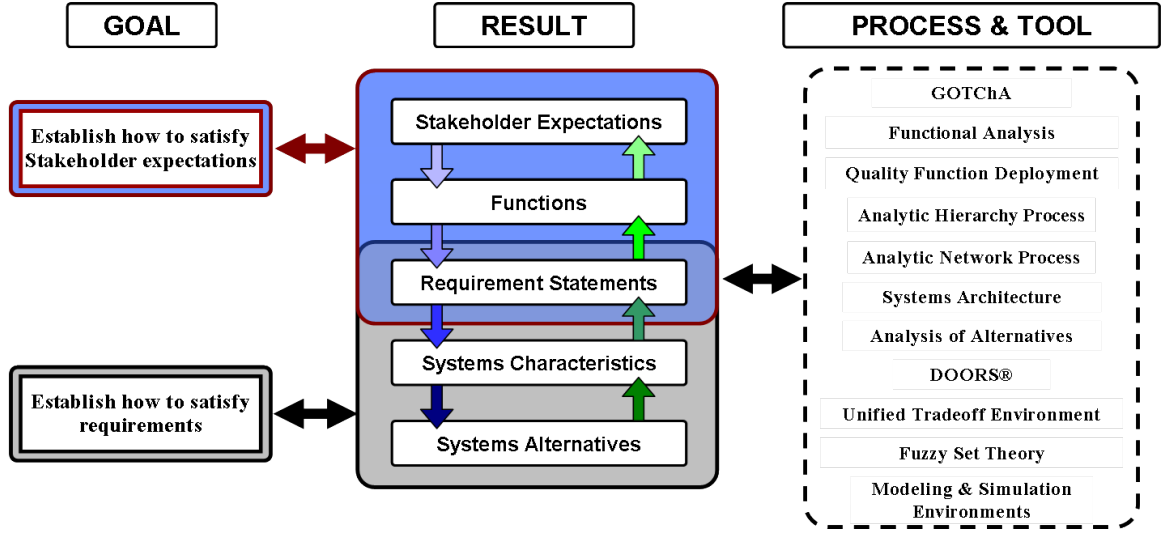


Figure 2.20: Simplified requirements methodology activities and tools.

the steps as part of the proposed methodology. In this figure the observations are leading to the research areas, which are explored through research questions. The research questions were selected as the most fundamental ones, and when answered open the path to further exploration of the research areas.

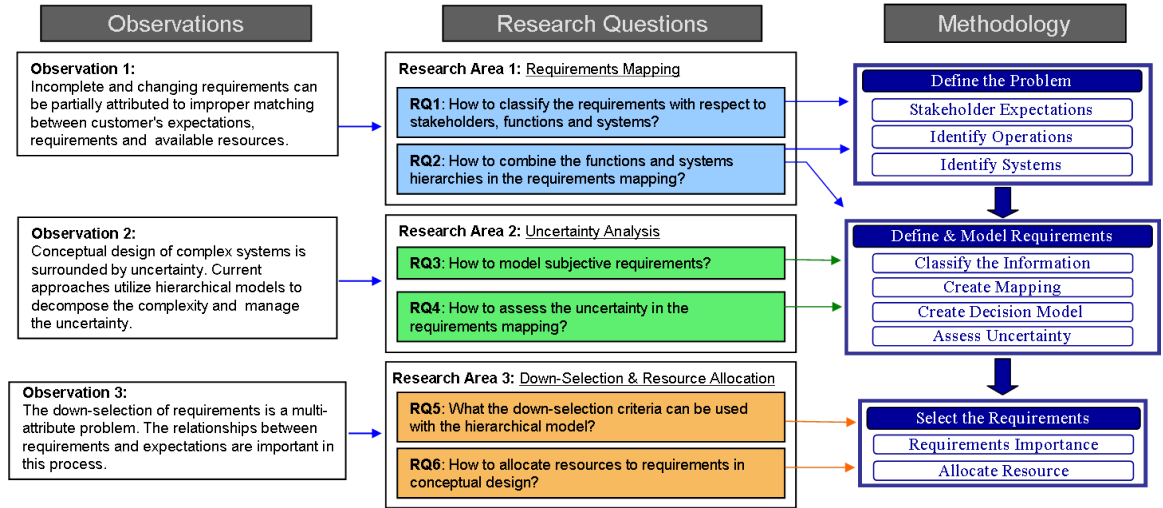


Figure 2.21: Relationships between observations, research questions and methodology.

The steps of the proposed methodology have been put in sequence in Figure 2.22. The intention of defining the methodology at this point is to frame the literature review by focusing on tools and processes associated to these steps.

The methodology includes three major activities (**A**, **B** and **C**). The activities are iterative, which mean that information acquired in any of the three activities can influence the results of previous design steps. The dotted arrows represent information stored or queried from management processes. These processes manage assumptions made by the design team and important results needed for subsequent system life cycle phase. The outcomes of the three major activities should match the results presented in Figure 2.20. Furthermore, the shaded steps represent areas where contributions from this thesis are expected to improve the current requirements methodologies. A formal design review between the stakeholders and the design team is conducted after a few iterations of the proposed methodology. The goal of the design review is to ensure that the selected requirements are matching the stakeholders expectations. Following this milestone, the design team will have a set of requirements that can be used to directly pursue the conceptual design or the create a Request For Proposal for potential contractors. Finally, the “*Verification and Validation Feedback*” loop implies the presence of iterative processes during the conceptual design that brings more information to the stakeholders and the design team in order to verify and validate the requirements.

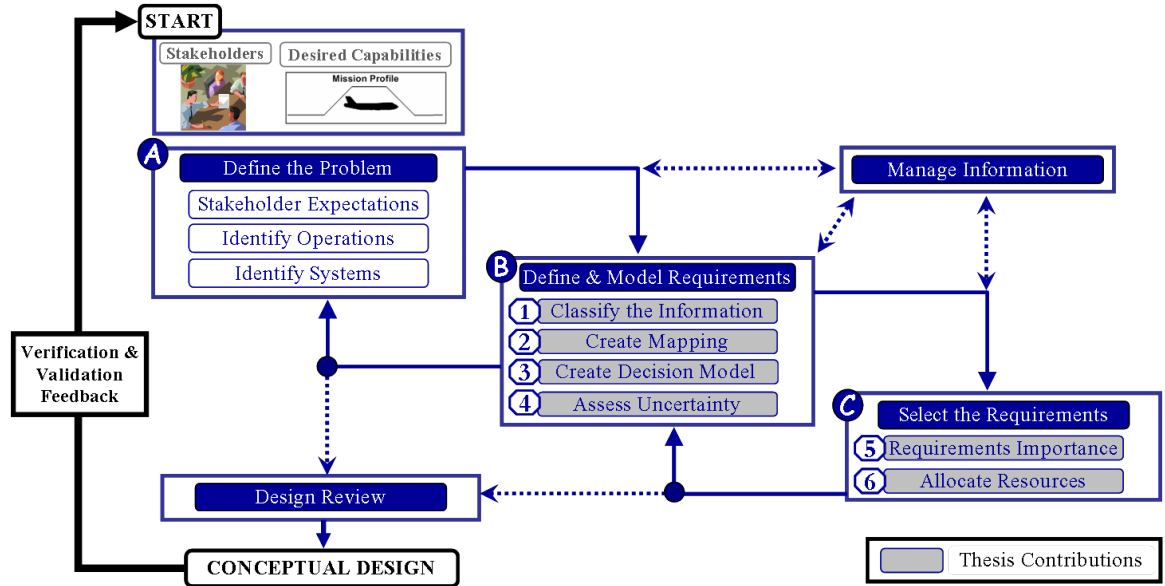


Figure 2.22: Proposed methodology.

Chapter III

LITERATURE REVIEW

The literature review addresses tools related to the requirements definition, modeling and selection processes. The processes are described while focusing on the four research areas described in Chapter 1: requirements mapping, uncertainty analysis, requirements down-selection and resource allocation. The problem definition section of the proposed methodology is not one of the main research areas of this study and it is discussed in Appendix A.

There are two objectives associated with this chapter. The first objective is to review the state-of-the-art tools and processes used in current requirements methodologies, and the second objective is to identify how these techniques can be used to improve the current requirements methodologies. An outline of the literature review by research areas is listed as follows:

I. Classification of Requirements

- i. Types of Requirements
- ii. Existing Taxonomy

II. Requirements Mapping Techniques

- i. Decision Model - GOTChA Chart
- ii. Quality Function Deployment process (QFD)
- iii. Analytic Hierarchy Process (AHP)
- iv. Analytic Network Process (ANP)
- v. Unified Tradeoff Environment (UTE)

III. Requirements Uncertainty Analysis Techniques

- i. Sensitivity Analysis
- ii. Monte-Carlo Simulation

IV. Requirements Down-Selection & Resource Allocation

- i. Multi-Attribute Decision Making
- ii. Benefit-Costs-Risks Analysis

This list is a sub-set of options taken from a morphological matrix of requirements tools and processes, as illustrated in 3.1. The rows of this matrix correspond to different categories of

Requirements Mapping	Descriptive Mapping Tools	Affinity Diagram	Tree Diagram	Inter-relationships diagram	PERT
		Telelogic DOORS ^(®)	SYSML/UML	FFBD	Petri-Net
	Descriptive Mapping Process	GOTChA	Morphological Matrix	Other	
	Qualitative Relationships Tools	AHP	ANP	Utility Theory	Other
	Qualitative Relationships Process	QFD	Pugh Method	Other	
	Quantitative Relationships	Historical Data	Numerical Simulation	Surrogate Model	Other
Requirements Uncertainty	Quantitative Process	Unified Tradeoff Environment	Other		
	Tools	Analysis of Variance	Sensitivity Analysis	Monte-Carlo simulation	Bayesian Theory
	Process	Systems Dynamics	Grey Theory	Fuzzy Set Theory	Other
Requirements Down-Selection		Robust Design Method	Markov Chain	Other	
	Multi-Attributes Decision Making	AHP/ANP	TOPSIS	Weighted Average	Linear Mapping
		Other			
	Multi-Objectives Decision Making	Utility Function	Goal Programming	JPDM	Costs-Benefits Analysis
		Genetic Algorithm	Other		

Tool or Process discussed in literature review

AHP: Analytic Hierarchy Process

ANP: Analytic Network Process

FFBD: Functional Flow Block Diagram

GOTChA: Goals, Objectives, Technical Challenges and Approaches

JPDM: Joint Probability Decision Making

Secondary tool

PERT: Program Evaluation and Review Technique

QFD: Quality Function Deployment

SYSML: Systems Modeling Language

TOPSIS: Technique for Order Preference by Similarity to Ideal Solution

UML: Unified Modeling Language

Figure 3.1: Matrix of Alternatives for Requirements tools and processes.

tools per research area, while the columns of the matrix correspond to alternatives that could be used to achieve the research objectives. One can imagine that a methodology could be created by selecting at least one tool or process per category. The number of combinations of the various tools can be calculated by multiplying the number of alternatives for each category. For instance, the matrix of Figure 3.1 has 1,382,400 possible combinations of tools and processes. The green elements of the morphological matrix are discussed in details in this chapter.

3.1 Classification of Requirements

In requirements analysis, the action of regrouping requirements in different types is part of the classification process. Structuring requirements based on pre-established types reduces the ambiguity, and improves the traceability and consistency of system requirements. Furthermore, it provides a solid foundation for a requirement architecture, which improves the organization and communication of requirements between stakeholders. A good requirement architecture structures the problem into smaller and more manageable problems; it facilitates the understanding of the system behaviors, and it enables the design team to rapidly

recover information for system performance verification and validation.

This section presents different types of requirements from the requirement analysis literature. The first part of the section presents general types of requirements associated with customers or end-users of the system. The second part of the section describes technical types of requirements associated with the systems engineering domain.

3.1.1 Customers and End-Users Requirement Types

A current “Top-Down” approach to decompose complex systems implies starting with general and broad concepts (Top), and as the process proceeds the concepts get specific and precise (Down). This section describes “Top” level requirement types which are associated with customers and end-users of the system.

Different stakeholders have different visions of the problem, and each of these visions implies different solutions and system requirements. Identifying the main stakeholders of a system is a critical activity in requirement analysis. A brief list of stakeholders includes the end-users, corporate decision makers, design team or engineers, and any person interacting with the system manufacturing and operational deployment. There is a simple hierarchy embedded in this brief list of stakeholders. The list is based from the moment where the first interaction occurs between the stakeholder and the system. The first stakeholders for any project are the customers, which can be either end-users and/or corporate decision makers. They are also the most important because the system is meant to fulfill their needs by achieving a desired mission. For this reason, Kano defined a model based on three types of end-user and decision maker requirements, namely: **must-be**, **one-dimensional** and **attractive** requirements [88]. These types of requirements are represented in Figure 3.2.

This figure presents the degree of achievement of the system versus the customer satisfaction. **Must-be** requirements are the foundation of the system. They are essential to obtain the desired level of achievement demanded by the customers, and consequently they should not be subject to any trade-off. Must-be requirements are often taken for granted by the stakeholders; therefore they may not be explicitly stated at the beginning of the project. As a result, satisfying must-be requirements will not increase the customer satisfaction beyond

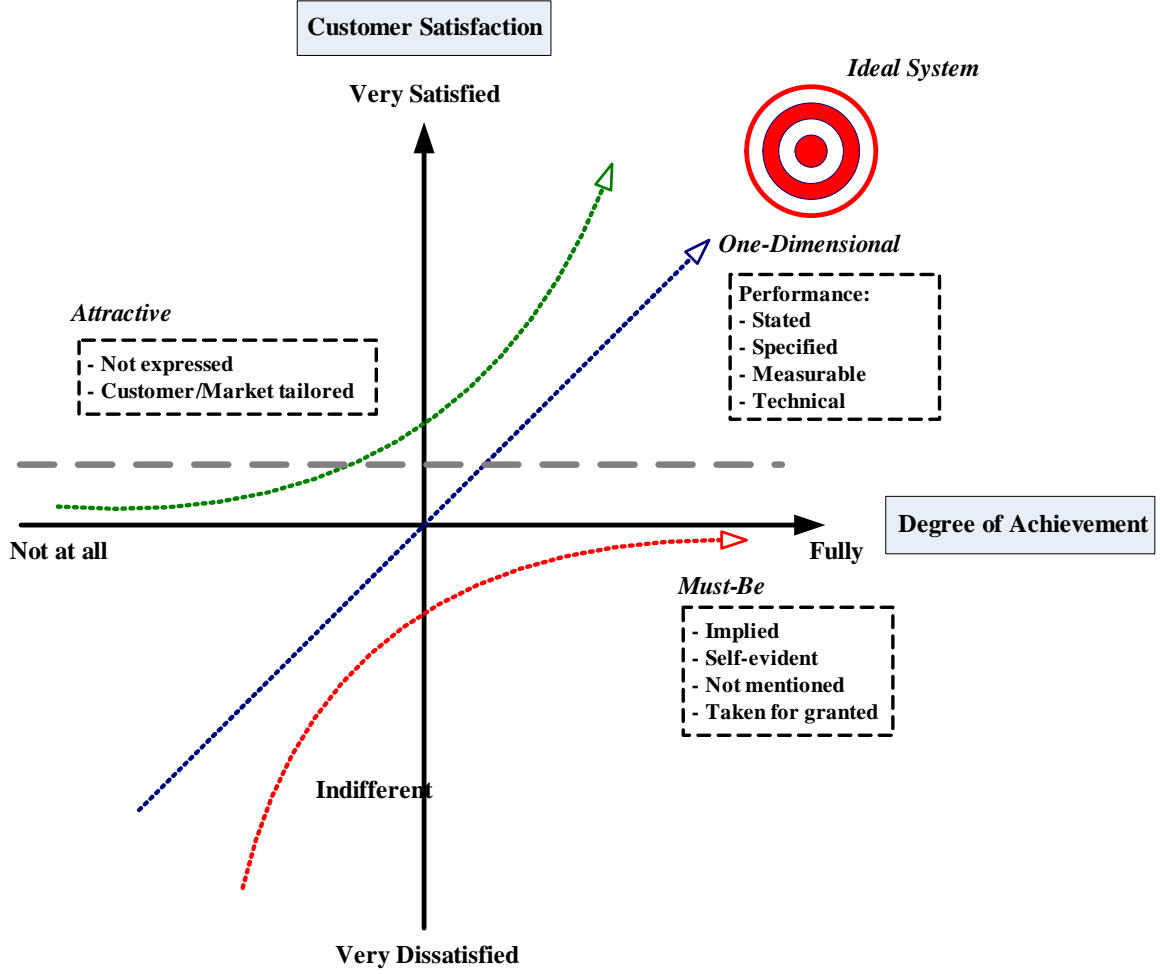


Figure 3.2: Kano Model - Requirements Types (*modified from [117, 106, 97]*).

a certain threshold. This threshold usually occurs when the customer is content with the performance achieved by the system. For instance during the design of an Unmanned Aerial Vehicle, the requirement that the UAV must fly is a must-be requirement.

The **one-dimensional** requirements represent a linear relationship between customer satisfaction and the level of achievement of the system. Generally, such requirements are explicitly stated by the customer which implies that they directly impact the level of customer satisfaction. Also one-dimensional requirements directly impact the system level of achievement because they correspond to technical and measurable specifications. In Figure 3.2, an ideal system maximizes the system customer satisfaction and level of achievement. However, in the current technical and economic context, where the amount of resources is

limited, engineers often have to reach compromise solutions by trading performances based on one-dimensional requirements.

The loiter time and the cruise speed for fixed wing UAV are good examples of one-dimensional requirements. A mission involving a long loiter period **and** a high-speed cruise implies a compromise solution in terms of the wing geometry. Assuming no morphing components in the wing geometry, the design team has to trade-off between the ideal loiter shape and the ideal high-speed shape.

The last type of requirement defined in Kano’s model is **attractive** requirements. These requirements are not expected nor expressed by customers. They are not essential for the achievement of the system since they are not specifically demanded by customers. Yet meeting attractive requirements has a great impact on the customer satisfaction because they are not initially expected by customers. The resources required to meet these requirements should not be taken from must-be or one-Dimensional requirements, which are essential for the achievement of the system. Examples of attractive requirements for UAV are: unexpected modularity (packaging) or aesthetic characteristics (color and shapes).

Similar to Kano’s model, Dieter identified four types of customer requirements: expecters, spoken, unspoken and exciter [45]. These types of requirements are also “Top” level, and they refer to actions (spoken & unspoken) and feelings (expectation & excitement) performed or expressed by the stakeholders. By comparing the Dieter and Kano requirements types, one can conclude that the following combinations are almost identical: unspoken = must-be, spoken + expecters = one-dimensional, and exciter = attractive requirements. This small comparison simply demonstrates that different authors described requirements based on different names and types.

The objective of this section is to introduce the most common types of requirements, and then regroup them into a taxonomy for the system design. This taxonomy is established in section 3.2. The next sub-section describes technical types of requirements specific to systems and requirement engineering.

3.1.2 Systems Engineering Requirements Types

As the project transitions from management to engineering, requirements become more specific and technical. In fact, for the design of a new system, requirements need to satisfy the characteristics presented in section 2.1.2.1, which implies less qualitative and more quantitative expression. This section presents types of requirements used by the systems and requirements engineering communities. More specifically the literature review includes requirement types from INCOSE, DoD, IEEE, Jackson[85] and Young[199]. The description of every type of requirement is divided in three parts. The first part starts with a definition of the requirement's type as adopted in this thesis. The second part describes the relationships between requirement properties and requirement types, and the third part discusses the importance of the specific requirement's type with respect to the customer satisfaction and the system level of achievement as described earlier in the Kano model.

The list of requirement types used in this research is depicted in Table 3.1. Since every organization has a different definition, this section will only discuss the most appropriate definition in the context of this thesis. The other definitions are documented as reference in Appendix E.

The first requirement type in the table is *Design*. As the term “design” describes an approach or process used to create something, in this case a system. The most appropriate definition selected for design requirement is taken from [Jackson, 1997] [85], and states the following:

“Design requirements are the attributes of the item needed to meet the performance requirements and constraints. These could include, for example, physical dimensions or power required.”

This definition is still general by not defining the types of attributes associated with design requirements. This suggests that design requirements are top-level requirements that will be refined or decomposed into other types. For example, an aircraft cruising at a “design” Mach number is a design requirement, however it also constitutes a performance requirement, which will be described later in this section.

Table 3.1: Types of Requirement used in System Engineering

Requirements	INCOSE [83, 82]	IEEE [81]	Young[199]	Jackson [85]	DoD[43]
Design	✗	✗		✗	✗
Constraint	✗	✗		✗	
Performance	✗	✗	✗	✗	✗
Derived	✗	✗	✗	✗	✗
Functional	✗	✗	✗		✗
Non-Functional	✗		✗		
Physical		✗			
Interface	✗	✗	✗	✗	
Environmental	✗		✗	✗	
Implementation		✗			
Allocated					✗

This small example illustrates the need to *trace* design requirements with other requirements, such as performance and constraint requirements. Tracing also helps to understand the impact of design requirements on the system capability. One property closely related to traceability is *consistency*. The consistency property is particularly important in order to track conflicts between requirements that occur during the design process. Generally, the number of conflicts depends on the complexity of the system, which also depends on the number of design requirements. Too many requirements may limit the design freedom of the system. Another factor limiting the design freedom is the requirement's level of *abstraction*. Design requirements need to be abstract enough so that they do not bias the system toward a specific solution or concept. However too much abstraction greatly increases design freedom and consequently the level of uncertainty. As a guideline, the level of abstraction of design requirements is defined in order to obtain *achievable*, *verifiable* and *validatable* requirements. Stakeholders that express and define design requirements are described in the next paragraph.

Customers or end-users may demand and define critical design requirements, such as the

Mach number for an aircraft. However, the main stakeholders of design requirements are the engineers in the design team. Customer will more than likely express performance criteria, which are based on design requirements. This decomposition step from performance to design is done during the conceptual design by the design team. During that phase, design requirements are used to establish the initial sizing and performance of the vehicle. Based on these results the level of achievement and customer satisfaction of the system can be investigated.

The level of achievement and customer satisfaction refer to the Kano model. Design requirements are a mix between *must-be* and *one-dimensional* requirements. They correspond to *must-be* requirement because the customer may not mentioned them explicitly, and at the same time they are essential for the overall achievement of the system. Yet, design requirements are often subject to trade-offs, which also classifies them as *one-dimensional*. They are subjected to compromise because of conflicts and constraints with other requirements.

While design requirements dictate the initial sizing of the vehicle, constraint requirements reduce the design space by imposing corporate, physical and functional limitations. Even though most organizations define constraint requirements in similar terms, this thesis uses the IEEE definition as reference [81]:

“*Constraint:* A statement that expresses measurable bounds for an element or function of the system. That is, a constraint is a factor that is imposed on the solution by force or compulsion and may limit or modify the design changes.”

There are two key elements in this definition that relate to important requirement characteristics. The first key element claims that a constraint requirement “*expresses measurable bounds for an element or function of the system.*” The constraints must be quantitatively defined, and they apply to specific element or function. The quantitative nature of constraint refers to the *verifiable* property, while the reference to an element or function refers to the *traceable* property of requirement. The second key element states that a constraint “*is imposed on the solution*”. The reference to a solution implies that some knowledge about the system is already acquired. As knowledge is gathered, the level of *ambiguity* is

reduced. Reducing the ambiguity about the system helps the engineers to define better constraints, so that the system is not limited based on false pretenses. Furthermore, one must be careful not to select a solution early in the design process, in order to meet the abstract property of requirements. During requirement analysis it is desired to maximize the design freedom, which implies a high-level of abstraction. Therefore, the element of solution on which the constraint is imposed has to be as general as possible in order to satisfy the abstract property. The last meaningful requirement property to constraint requirements is *consistency*. By definition, constraints indicate some level of conflict between two or more elements. Then, it is important for constraint requirements to be consistent with the other requirements and functions that they influence. The limitations imposed on the system by constraint requirements also impact the decision process of stakeholders.

Constraint requirements have multiple stakeholders. Corporate decision makers impose constraints on budget and schedule, engineers define performance, physical and technological constraints, and even end-users impose ergonomic and operational constraints. So every constraint requirement has at least one stakeholder, and every stakeholder may potentially impose constraints on the system. Consequently, the identification of constraint requirements can be conducted by iterating between stakeholders and constraint requirements. This process also indicates the influence of constraint requirements on customer satisfaction and the system's level of achievement.

Once again referring to the Kano model of customer satisfaction and system level of achievement, constraints are a mix between must-be and one-dimensional requirements. Must-be requirement because most of them are not explicitly stated by the customer. For instance the end-user may not be aware of the state-of-the-art or technological constraint, and one dimensional requirement because constraints imply compromise solutions and consequently trade-offs on the system's level of achievement. Constraint and design requirements are more general, they provide a global view of the design space. The next requirement types are more specific to some areas of the design space, the first type being discussed is performance requirement.

Performance requirements are probably the first type of requirement that comes to mind

during the requirement elicitation phase. There are a large number of performance requirements, and they are present at every level of the system design. For these reasons, performance requirements are often confused with other types of requirements. In order to clearly differentiate performance requirements, this thesis utilizes the DoD definition which states the following [43]:

Performance requirements: “*The extent to which a mission or function must be executed; generally measured in terms of quantity, quality, coverage, timeliness or readiness. During requirements analysis, performance (how well does it have to be done) requirements will be interactively developed across all identified functions based on system life cycle factors; and characterized in terms of the degree of certainty in their estimate, the degree of criticality to system success, and their relationship to other requirements.*”

This definition presents important points relating performance requirements with requirements properties. The performance of a system is verified “*in terms of quantity, quality, coverage, timeliness or readiness.*” They are probably the more straightforward requirements to *verify*, and many times the customer satisfaction depends on their achievement. Consequently there must be no *ambiguity* regarding the need and definition of the requirement. Also, in the DoD definition the “*degree of certainty in their estimate*” indicates that uncertainty is present in the requirement definition. One way to reduce the ambiguity is to *trace* requirements to functions. The DoD expresses the traceable property by mentioning that “*requirements will be interactively developed across all identified functions.*” Therefore functions and performance requirements are directly linked together, and for every function there must be a requirement and vice versa. Furthermore, the requirements must be *achievable* in the project technical and economical context. The level of achievement of performance requirements greatly impacts the success of the system. The design team must pay particular attention so that performance requirements are achieved with the current set of technologies available during the system development. Ultimately, the success of the system is based on the level of satisfaction of all stakeholders, from design to operations.

Stakeholders of performance requirements can be found at almost every phase of the system life cycle. Fundamentally, a system “**performs**” a task or activity. Consequently, initial customers or end-users express the overall system performance early on in the project. As the design progresses the system is divided in sub-systems, which relate to more technical stakeholders like engineers. These stakeholders also expect a certain level of performance from the system. Therefore, the overall system has to meet the expectation of all stakeholders because performance requirements are at the front line of the design process.

In relation to the Kano model customer satisfaction and level of achievement, performance requirements are purely one-dimensional based on three criteria. First, the customers express them at the beginning of the project. Second, performance requirements directly impact the system level of achievement and the customer satisfaction. Third, trade-offs between performance requirements may be required to achieve the desired overall system performance. These trades often create new requirements called derived requirements.

As the name suggests, derived requirements originate from higher-level requirements or functions. Since every requirement is based on other requirements or functions, the notion of derived requirement can theoretically be applied to all requirements. This generalization adds uncertainty when defining this type of requirement. This emphasizes the need for a proper definition of derived requirements. Furthermore, derived requirement is the only type of requirement defined by all entities listed in Table 3.1. This suggests that derived requirements are difficult to identify and define, and also it underlines their important role in requirements analysis and system design.

Young provides a definition of derived requirements that clarifies the subjectivity, and it also suits well the context of this research [199].

*“**Derived requirement:** is one that is further refined from a higher-level requirement or a requirement that results from choosing a specific implementation or system element. In a sense all requirements are derived from the system need; thus the derived distinction tends to have little significance. However, many systems engineers distinguish between externally identified requirements and requirements that are derived under the control of the engineer.”*

In this thesis, it is assumed that derived requirements are “*derived under the control of the engineer*”. Borrowing an example from the DoD definition of derived requirement, an aircraft design for long range or high speed missions implies a structural weight reduction as derived requirement [43]. Then this derived requirement has to be identified and classified in order to meet the important requirement characteristics.

Important requirement characteristics for derived requirements are traceability, consistency and abstraction. By definition, derived requirements need to be traced to their respective higher level requirements or expectations. That facilitates the understanding of the problem when requirements are modified or removed from the hierarchy. Also, derived requirements may evoke conflicts resulting from trade-offs with other requirements. Therefore, derived requirements must be consistent with respect to the other requirements. By following the path from derived to higher-level requirements, the design team must be careful to keep derived requirements as abstract as possible. Especially since derived requirements are said to be the “*results from choosing a specific implementation or system element*” [199]. Respecting these important requirement’s characteristics reduces the ambiguity of the design problem, and it ultimately helps to satisfy the stakeholders expectations.

Generally, derived requirements are indirectly linked to stakeholders because they are derived from higher-level requirements. Consequently the design team is the main stakeholder, and its goal is to assure that all performance requirements are satisfied by trading performance and resources with derived requirements. Even if derived requirements may be perceived lower in the hierarchy than performance requirements, not satisfying them negatively impacts system performance, and consequently reduces the customer satisfaction.

The Kano model represents the customer satisfaction versus the level of achievement of the system. In this context, derived requirements are one-dimensional because they impact both customer satisfaction and level of achievement. However, they differ from one-dimensional requirements since they are not initially expressed by the stakeholders. Derived requirements are defined during the requirements analysis, more specifically while performing trade studies with higher level requirements. Therefore, it is usually more difficult to elicit derived requirements, and some of them may be overlooked in the process. One way to

minimize this problem is to make sure that all functional requirements are fulfilled, which is the next type of requirement discussed in this section.

During the requirements elicitation process, functional analysis is a technique frequently used to decompose the complexity of the system. It helps design teams to improve their understanding of the problem by listing fundamental functions of the system. This activity is described in more detail in section A.1. One basic principle of functional analysis states that there must be a requirement for every function of the system. These requirements are then called functional requirements. The DoD definition of functional requirement is adopted for the current research [43]:

***Functional Requirements:** “The necessary task, action or activity that must be accomplished. Functional (what has to be done) requirements identified in requirements analysis will be used as the top-level functions for functional analysis.”*

Functional requirements are generally the first type of requirement elicited during the design of a new system. They refer to “what” the system must accomplish. It is often more intuitive for the design team to start by defining functions, and then generate functional requirements. The functions resulting from functional analysis constitute a good starting point for requirements analysis. A function is defined as a verb followed by a noun. For instance, **provide lift** for the vehicle, is a top-level function for an aircraft system. Consequently, top-level functions are used as a foundation for functional and requirements hierarchies. Due to the importance of functional requirements, it is important to verify requirements with respect to the characteristics discussed in section 2.1.2.1.

All the requirements properties are needed to define good functional requirements. The most important properties are: traceability, consistency, unambiguity, and abstraction. First the traceability property is essential due to the multiple levels of functional requirements. These requirements need to be traced to the functions that they are meant to fulfill, and to the requirements that are performing the functions. Second, consistency is achieved by minimizing the number of conflicts between requirements and by mitigating the impact of

conflicts on the system. This activity also provides a better understanding of the system, which helps to reduce the ambiguity. Functional requirements also tend to be vague which add uncertainty to the design. At this stage, reducing ambiguity is done by gaining more information and knowledge about the system. Achieving the unambiguity property is accomplished by defining functional requirements as verifiable, validatable and achievable. Finally, the abstraction property relates to the design freedom of the engineering team. On the one hand, it is desired to have abstract functional requirements to increase the design freedom during the conceptual design phase. On the other hand, large design freedom implies a large number of design options which might create confusion and uncertainty while trying to select a concept. One technique to mitigate this problem is to understand who are the functional requirements stakeholders.

There is a broad spectrum of stakeholders for functional requirements, mainly because there are multiple levels of functions. Starting with requirements issued from top-level functions, these functional requirements are generally omitted by customers or end-users because they are intuitively expected. Furthermore, top-level functional requirements result from the requirements analysis of the system. Consequently the design team is the main stakeholder of functional requirements. At lower levels of the requirements hierarchy, functional requirements are becoming more specific, hence they may be explicitly demanded by customers, end-users or operators. In this instance, it is difficult to assign stakeholders to the entire range of functional requirements, because there are functional requirements for every stage of the product life cycle. However, identifying stakeholders of functional requirements is helpful to quantify the impact of the requirement on the overall customer satisfaction.

Once again referring to the Kano model of customer satisfaction and level of achievement, top-level functional requirements are *must-be* requirements. They are fundamental for the achievement of the system, and often not even stated by customers or end-users. Lower level functional requirements include *must-be* and *one-dimensional* requirements. During requirements elicitation, the design team should distinguish essential functional requirements from the ones that can be subject to trade-offs. Requirements subject to trade-offs are *one-dimensional*, which indicate a compromise between the level of achievement and the

customer satisfaction. While functional requirements establish “what” the system must do, non-functional requirements define the boundaries of the design space.

Non-functional requirements (NFR) are often viewed as limitations or constraints for other requirements. They are also referred to as quality attributes, “ilities” or specialty engineering requirements [199, 35]. Non-functional requirements provide valuable information and knowledge about the system which may end up to be critical for decision makers. Cysneiros et al. provided the following definitions for non-functional requirements [35]:

Non-Functional Requirement: “NFRs, as opposed to functional ones, do not express any functionality to be implemented in the future information system. On the contrary, they express behaviour conditions and constraints that must prevail.”

“NFRs can be seen as requirements that constrain or set some quality attributes upon a functional requirement.”

This definition states that non-functional requirements “*express behaviour conditions and constraints*” of the system. A behaviour condition represents how the system performs in a specific environment, for example usability and portability. A non-functional constraint limits the system performance, such as the efficiency of an engine or the reliability of a turbine’s blades. A third category can also be added, the physical non-functional requirements. These requirements include volumetric considerations such as modularity, modifiability, and capacity of the system. A small list of non-functional requirements is depicted in Table 3.2, they are regrouped by behaviour, constraint and physical conditions.

Table 3.2: Non-Functional Requirements [199]

Behaviour	Constraint	Physical
Portability	Designability	Modularity
Testability	Efficiency	Modifiability
Usability	Reliability	Capacity
	Maintainability	

Some requirement properties are more important while defining non-functional requirements. Since non-functional requirements represent behaviors or constraints, they should be

traceable and consistent with requirements that they characterize or limit. Traceability and consistency are the most important properties of non-functional requirements. It is also important to verify and clarify non-functional requirements. By definition, a constraint already implies a limit that is verifiable during the design. However, the numerical value of that constraint may be uncertain, or based on incomplete information. Therefore, it is important to reduce the ambiguity associated with non-functional requirements. The ambiguity can also be reduced by knowing the stakeholders of the requirements.

Analyzing stakeholders associated with non-functional requirements also provide valuable knowledge about the system. On the one hand, customers or end-users of the system represent stakeholders of behavior conditions such as usability. On the other hand, the design team manages constraints or physical non-functional requirements regarding the design of the system. In general, non-functional requirements are more subjective than the other types of requirement, therefore knowing where to get additional information by asking stakeholders greatly improves the chance of meeting the customer expectations.

Once again the Kano model can be used to interpret the relationship between non-functional requirements and customer satisfaction. Non-functional requirements constraining the system are mainly one-dimensional. At the same time they affect the level of achievement of the system, and their implied limitations are directly related with the customer satisfaction. For example if the required efficiency of the engine compressor is set to 80%, a lower value will definitively impact the performance of the system, and consequently it will reduce the customer satisfaction. Regarding the behavior and physical non-functional requirements, more than likely these requirements are perceived as attractive by the customers and end-users. They may not be expressed nor demanded by the customer, but the surprise factor has great potential of increasing the customer satisfaction. One can remember having been positively surprised by some usability or modifiability features that are often present in new car models. These features will not make you buy the car, but they help to distinguish from the competition if the customer hesitates between two similar models. For complex systems, the coupling of functional and non-functional requirements helps the design team to reduce the design space from a very large number of possibilities to a manageable number

of concepts. These concepts involve more specific types of requirements, such as physical requirements.

Physical requirements are more specific than functional and non-functional requirements. Physical requirements require a pre-selection of potential solutions or concepts for the systems. Since the design team selects solutions toward the end of the requirements analysis process, physical requirements are generally the last type of requirement to be defined in conceptual and preliminary design. This thesis utilizes the IEEE definition of physical requirement which states the following [80]:

“Physical requirement. A requirement that specifies a physical characteristic that a system or system component must possess; for example, material, shape, size, weight. ”

This definition is relatively simple, it includes requirements related to the system sizing such as dimensions and masses. However, the difference between physical requirement and physical non-functional requirement may create some confusion. Physical non-functional requirements are *conditions* related to the physical nature of the system, like modularity. For instance, the modularity of components is counted by the number of possible configurations, while physical requirements are used for each configurations. This example demonstrates that physical requirements also need to respect important requirement properties such as traceability, consistency, and achievability.

Most of the time, quantitative values are assigned to physical requirements, which make them easier to verify and validate during the design process. Some of these quantitative values may have been explicitly demanded by customers or end-users. For example, if the system needs to fit within a certain volume, then the maximum dimensions of the components need to respect this overall volume. Consequently, it is important to trace physical requirements with their respective higher level requirements, so that all customer expectations are fulfilled, and that no violation of other requirements is allowed. There may exist potential conflicts between physical dimensions if the tolerances are not respected between components of the system. Therefore, physical requirements need to be consistent

so that the integration of parts or systems proceeds smoothly. The design team also has to make sure that the level of tolerance required is achievable with the current manufacturing processes and tools. On the one hand, if the tolerances are too small, it will be difficult to measure, produce and integrate the components. On the other hand, if the tolerances are too large, it may create conflicts between requirements and degrade the performance of the system. To avoid these problems, defining physical requirements then necessitate good management and communication between stakeholders.

As mentioned earlier, some physical requirements are directly demanded by the customer in order to meet a given volume. These requirements often refer to a non-functional aspect of the system such as packaging, transportability, usability or modularity. In this case, the stakeholders are the customers or end-users. However, most physical requirements are derived from functional and performance requirements. Consequently, the design team usually defines and manages physical requirements. More specifically, physical consistency of the system is handled by engineers in charge of computer models and technical drawings. As engineers model the different systems, they often have to create interface to link components. Depending on the system or component, these interfaces are also subject to specific requirements called interface requirements.

The objective of an interface is to create a continuity between systems and components. There are two types of interface: functional and physical. Jackson states that “*an interface is a boundary between two system elements*” [85]. This definition implies that the systems have been pre-selected by the design team. Consequently interface requirements are generally defined and used in preliminary and detail design; however it is good practice to elicit them early in the design process in order to anticipate and reduce the number of potential costly design changes. This thesis uses the IEEE definition of interface requirement, which states the following[80]:

Interface requirement. *A requirement that specifies an external item with which a system or system component must interact, or that sets forth constraints on formats, timing, or other factors caused by such an interaction.”*

An interface requirement defines how an external component interacts with the system. That component can interact either functionally or physically. Electrical power is one of the most common functional interfaces, while a physical interface represents any structures required to link components and systems. These relationships and interactions are then captured by requirement properties such as traceability and consistency.

Even if interface requirements are defined later in the design process, they still need to meet important requirements characteristics as illustrated in Figure 3.3. Interface requirements correspond to inputs and outputs of the system. Uncertainty in the interfaces may create conflicts with other requirements and sub-systems. Therefore, it is important to reduce the *ambiguity* so that interface requirements are well understood, *verified* and *validated* as the design progresses. The comparison of the interface requirements with their threshold values provides a good indication of the system efficiency. If a system efficiency is too low, then interface requirements are good starting points to debug the system. The debugging process consists of *tracing* unfulfilled interface requirements with their respective functional or physical requirements. The traceability characteristic provides valuable information about the system completeness, since functions represent high-level requirements, and interfaces represent lower level requirements. This activity may also highlight potential conflicts or trades that the team will have to mitigate during the design process. The reduction of the number of conflicts translates into *consistent* interface requirements and ultimately a better understanding and satisfaction of the system by the stakeholders.

The design team is the main stakeholder of interface requirements. Since interface requirements are defined following the selection of a specific system architecture, they are controlled and managed by engineers in charge of the system assembly and integration. These engineers are also responsible of communicating interface requirements to the system developer, so that the proper inputs and outputs are taken into account in the system software or hardware. In this case, the level of system achievement and customer satisfaction depend of how well interface requirements are fulfilling higher level functional or physical requirements.

The last type of requirement discussed in this section is an environmental requirement.

In some cases, environmental requirements are considered as constraints, non-functional requirements or even design requirements while referring to operational conditions. There exists some natural ambiguity surrounding the classification of environmental requirements. Some environmental requirements affect the performance of the vehicle, while others are associated with the corporate cultural environment. Jackson states that “*the system engineer should assure that all requirements are satisfied under the appropriate environments and combinations of environments*” [85]. This quote clearly expressed the importance of environments in requirement analysis and design. This thesis utilizes Young’s definition of environmental requirements, which states the following [199]:

“Environmental Requirements: *These are requirements that result from the physical setting and social and cultural conditions of the system development effort and the setting in which the system or software will be used.”*

This definition encompasses a broad range of environments, from physical to social environments. On one hand, physical environmental requirements are relatively common and consequently well understood in design. They include: “temperature, pressure, shocks, vibrations, etc” [85]. On the other hand, social and cultural environmental requirements are not as crisply defined, and most of the time they are reflected through decisions made by corporate decision makers or stakeholders. For example, if a company has been working with the same structural airframe configuration for the past decades, then it will probably be “required” for new systems to use on the same airframe configuration. Nevertheless some element of subjectivity, environmental requirements are also subjected to requirements properties.

A good definition of environmental requirements includes the following characteristics: verifiable and validatable, unambiguous, traceable, and consistent. While testing the system, engineers must be able to *verify* the specific environmental conditions. The system performances can then be *validated* and compared to their targeted design conditions. Consequently, environmental requirements need to be precise and *unambiguous*, so that no noise conditions interfere with the data collection. A reduction of performance, caused by specific

environmental conditions, can be disastrous for the system. It is important for the design team to *trace* these environmental requirements with other requirements affected by the surrounding conditions. Examples of affected requirements are non-functional requirements such as efficiency, reliability and safety. Furthermore, a reduction of performance can also cause conflicts between requirements. In order to mitigate the number of conflicts, the requirements definition must be *consistent* with higher level requirements already established in the system. The mitigation of conflicts is usually handled by the respective requirement stakeholders.

Two main stakeholders can be identified for environmental requirements. First, the design team is responsible for physical and operational environmental requirements. The engineers must determine critical operational conditions that can potentially occur during the system life cycle. Once identified these conditions can be translated into environmental requirements. Second, corporate decision makers impose, implicitly or explicitly, social and cultural requirements upon the system design. Implicitly when requirements are based on company history of designing and producing system. Explicitly when social and cultural requirements are specified during the design process, for instance any requirements related to the team dynamic. Both physical and social environmental requirements may have an impact on the customer satisfaction.

Environmental requirements may have great influence on the customer satisfaction. It is expected that a system perform optimally under control conditions, however when some undesired environmental conditions occur the system performance may greatly decrease. Since physical environmental conditions are affecting the performance of the system, they have a great impact on the customer or end-user satisfaction. On the other hand, social environmental conditions will have a great impact on the level of achievement of the system. These requirements will affect the design of the system and sometimes even bias it toward a specific configuration.

Other types of requirements are also mentioned in the literature and listed in Table 3.1, implementation and allocated requirements. These types of requirements are not described in detail because they are assumed already covered by other types. The IEEE definition of

implementation requirement is the following [80]:

“Implementation requirement. *A requirement that specifies or constrains the coding or construction of a system or system component.”*

This definition implies that implementation requirements can either be constraint, non-functional or environmental requirements. Constraint and non-functional requirements can represent specifications or limitations on the system. It can also be considered an environmental requirement if a required implementation is the only one available in the company. The same type of observation can be done for allocated requirements. The DoD defines an allocated requirements as follow [43]:

Allocated requirements: *“A requirement that is established by dividing or otherwise allocating a high level requirement into multiple lower level requirements. Example: A 100-pound item that consists of two subsystems might result in a weight requirements of 70 pounds and 30 pounds for the two lower level items.”*

One can observe striking similarity between allocated and derived requirements. It is difficult to imagine a case in which a requirement would be allocated but not derived. In order to reduce the redundancy between types of requirements, implementation and allocated requirements are not part of the proposed taxonomy of this research.

To conclude this section, Figure 3.3 summarizes the relationships between the requirement types and the requirement properties discussed in section 2.1.2.1.

	Verifiable	Unambiguous	Traceable	Consistent	Abstract	Achievable	Validation
Design	●	●	●	●	●	●	●
Constraint	●	●	●	●	◐	○	○
Performance	●	●	●	◐	◐	●	◐
Derived	◐	◐	●	●	●	○	◐
Functional	◐	●	●	●	●	◐	◐
Non-Functional	◐	◐	●	●	○	○	○
Physical	◐	◐	●	●	○	●	●
Interface	●	●	●	●	○	◐	●
Environmental	●	●	●	◐	○	○	●
Level of importance: ● ◐ ○ High Medium Low							

Figure 3.3: Summary of requirement types versus properties.

Assuming that all requirement types are equally important, it is possible to determine a ranking of requirement properties. The four most important properties that engineers must pay special attention to while defining requirements are, from most important to less important: *traceable*, *consistent*, *unambiguous* and *verifiable*. These properties help the design team to better understand the problem, and consequently to design quality customer oriented systems.

Regarding the requirement types, it is important to understand that they are not all at the same level in the requirement hierarchy. Some of them are more general, while others are more specific to parts of the system. The order in which the requirement types are discussed in this section may not be the best order for a requirement hierarchy. The next section will discuss approaches used to create requirement hierarchy, which will lead to the creation of a requirement taxonomy for aerospace conceptual design. This taxonomy will then be applied to the proof of concept.

3.2 Taxonomy of Requirements

The classification of requirements requires two fundamental activities. The first activity consists of creating groups, which is achieved by using the different types of requirements defined in the previous section. The second activity involves the creation of relationships between the groups of requirements. The objective of the relationships is to organize requirements in a logical and efficient manner. Consequently, the synthesis of all the relationships gives the taxonomy.

The word taxonomy is defined by the Merriam-Webster dictionary as: “*the study of general principles of scientific classification*” [122]. The main goals of a taxonomy are to organize, manage, store and recover critical information of a project, in order to provide more structure during the requirements identification process, and at the same time to decompose the problem complexity.

This section is divided in two parts. The first part describes fundamental properties of a taxonomy, while the second part reviews existing taxonomies, in order to determine if a new taxonomy is needed to classify the requirements.

3.2.1 Taxonomy Properties

In order to create a taxonomy some guidelines must be followed. Gershenson and Stauffer (1999)[58] synthesized previous research on taxonomy. They state that a good taxonomy should follow three properties: completeness, perceptual orthogonality, and parallel structure.

A taxonomy is complete when all the project's requirements are identified and defined. Rounds and Cooper (2002)[152] call this property comprehensiveness, and they state that sufficient information must be gathered in order to provide a good understanding of the product and its life cycle. This is due to the fact that more information decreases the system level of uncertainty. However, gathering a large number of requirements can be very time consuming, and too much information may confuse the stakeholders during the selection of a critical set of requirements. Furthermore, the initial set of requirements is not static, and as the design progresses requirements will evolve and new requirements will be added; therefore the taxonomy must be adaptable, and potentially evolves with the system. The next step is to structure the taxonomy referring to the second property.

The second property is called perceptual orthogonality or mutual exclusiveness. The objective is to classify and manage requirements within independent categories. In the taxonomy nomenclature, these categories are called taxons. The taxons are system dependent, and can be based on the system life cycle phase or result from functional analysis or the affinity diagram. Perfect orthogonality is difficult to achieve, and requirements will most likely be categorized in more than one taxon. For instance assume an aircraft requirement taxonomy with two major taxons being "Design requirement" and "Performance requirement", as shown in a hierarchical tree in Figure 3.4. The customer specifies a cruise Mach number of 0.8. Since this requirement is directly from the customer it is an important design requirement, however it is also a performance requirement. In this case Mach number can be put in both taxons, but there must be a link between the two taxons so that any modification is reflected in both places. Once the major taxons are identified, it is important to verify that they have approximately the same uniformity which constitutes the third taxonomy property.

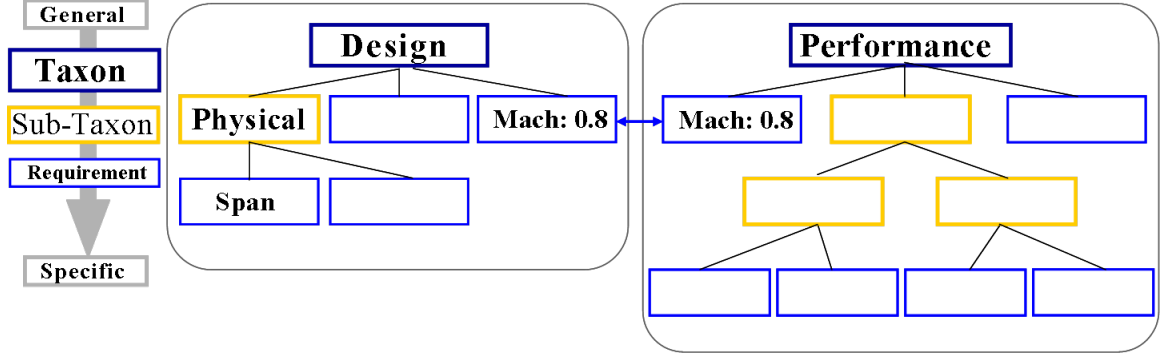


Figure 3.4: Taxonomy properties.

The third property characterizes the parallel structure and uniformity of the taxon. The parallel structure of a taxonomy refers to its hierarchical format. The objective is to facilitate the management and the understanding of the taxonomy. Each taxon starts with top-level requirements which are more general, and the hierarchy expands to more detail and specific requirements, as illustrated in Figure 3.4. This flow of information, general to specific, constitutes a top-down approach. Gershenson and Stauffer (1999) [58] state that *each major taxon of the hierarchical taxonomy should have the same **level of abstraction***. The concept of level of abstraction is based on a reference, something is more or less abstract by comparison to a reference. For this research, the reference could be a mental image of the concept to be designed, for a transport aircraft the transition between high to low level of abstraction is shown in Figure 3.5. The first levels are uncertain either because of a lack of knowledge or to keep the design space as open as possible. As requirements are identified the system is refined, less abstract, and the mental image of the concept is getting crisper. Therefore the selection of taxons with the same level of abstraction must be done prior to the creation of the hierarchical format.

Furthermore, Rounds and Cooper (2002) [152] argue that the uniformity of the taxon is also important while using the taxonomy in a decision making context. Because of the hierarchical format, higher level requirements (high-level of abstraction) are often considered more important than lower level requirements (low level of abstraction). This is generally due to the fact that high-level requirements have the potential of influencing many lower level requirements. The next section describes some existing taxonomies found in the literature.

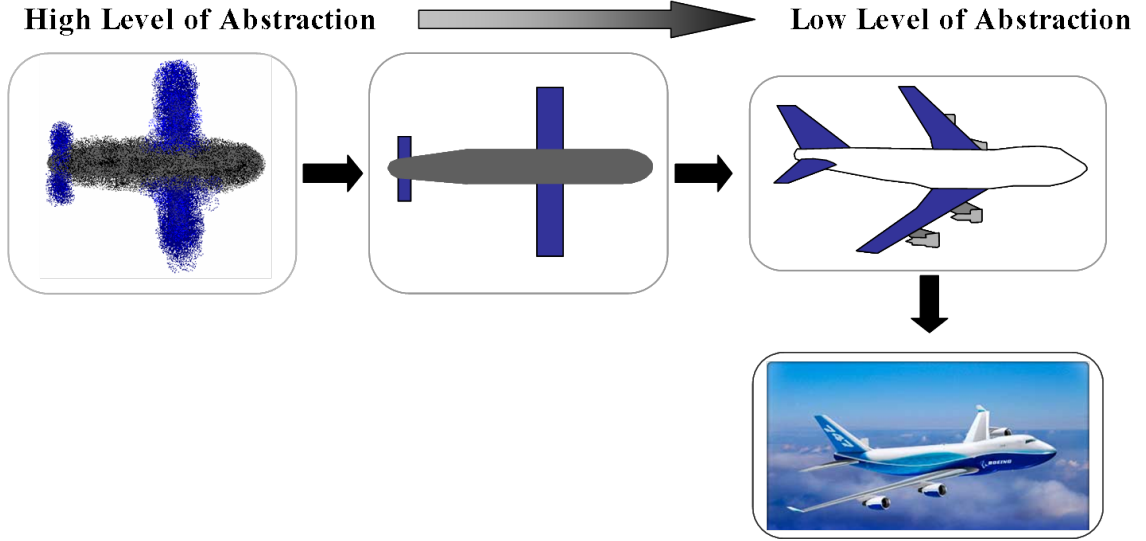


Figure 3.5: Concept level of abstraction ([20]).

3.2.2 Existing Taxonomy

There are examples in the literature of techniques used to organize and manage requirements, to some extent these approaches can be viewed as taxonomy. Depending on the system, the taxonomy structure changes which make it difficult to create a general taxonomy applicable to every system. This section is divided in two parts, the first part presents a general taxonomy by Gershenson and Stauffer [58, 57], while the second part discusses the process of classifying requirements in systems engineering.

Gershenson and Stauffer introduce their general taxonomy by starting with the user contexts. The user context is the starting point of the requirement structure, it includes all the stakeholders of the project. This initial structure is illustrated as a requirement cube in Figure 3.6. The fundamental categories of the requirement cube are based on Ullman's taxonomy for mechanical design, which are: the *environment*, the *problem*, and the *process* [178]. These categories are translated into the cube's dimensions as the user context (*environment*), the product specifications (*problem*), and the product definition process (*process*). The customer information leads to the definition of product specifications, while the processes provide a path to achieve the specifications. To summarize the cube analogy, it represents the fundamental components included in a requirement taxonomy, which include

the knowledge of the stakeholders, a good understanding of the product specifications and the definition of the processes required to design and manufacture the system. The next paragraph describes the user context dimension.

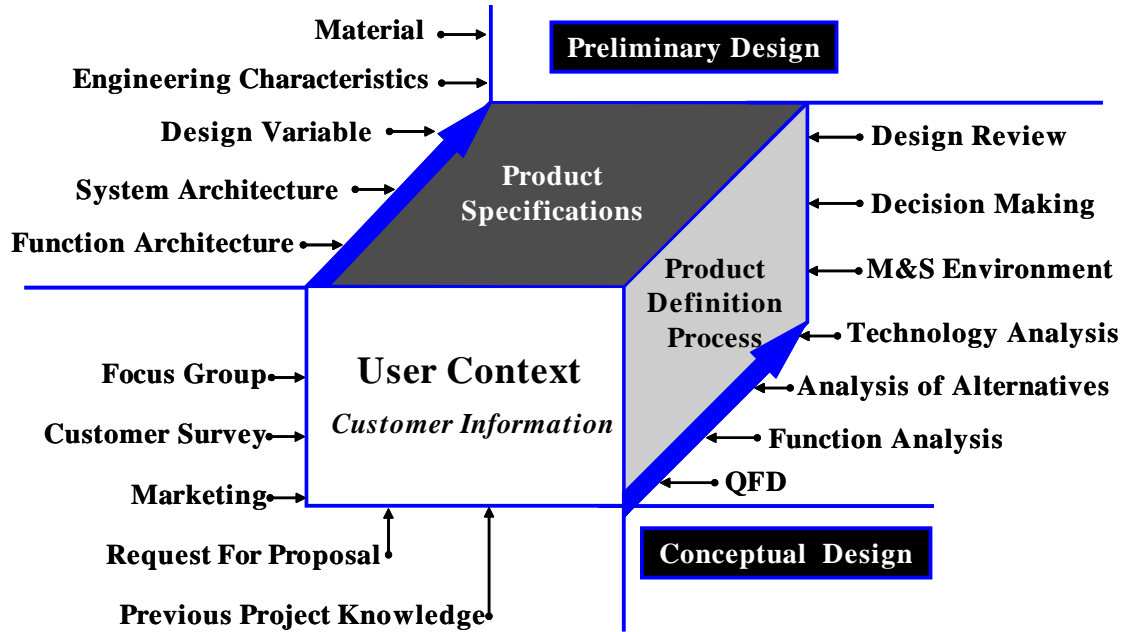


Figure 3.6: Requirement cube (modified from [58]).

The user context of the requirement taxonomy is divided in four categories representing the main stakeholders of a system: end user, corporate management, regulatory entities and engineering team. Each of these categories or taxons involves a significant number of requirements. The first part of this discussion involves a brief description of the different user context. The second part describes an example of a corporate taxonomy including its structure.

End user requirements include needs and expectations specified by the customers. These types of requirements were discussed in detail in the Kano's model of section 3.1.1. **Corporate** requirements include the other stakeholders requirements related to the business and product life cycle. This taxon involves a wide range of individuals from marketing to the system retirement. Since many companies have similar corporate structure, the sub-taxons of the corporate context can be generalized to a large number of systems. However the same generalization cannot be done for the regulatory and technical contexts, which are

fundamentally system dependent. **Regulatory** requirements include government and industry standards and regulations regarding environmental, safety and political requirements. These requirements usually depend on the type, class and operating conditions of the system. **Technical** requirements are based on the different engineering disciplines synthesized in the system. For instance, aerospace systems include disciplines such as aerodynamics, propulsion, structures, etc. Each of these disciplines includes specific requirements which makes this taxonomy system dependent. These four user contexts represent the first dimension of the overall requirements taxonomy. These contexts are then developed in the product and process dimensions. Each taxonomy then includes multi-level taxons in order to further decompose the system complexity.

An example of a corporate requirements taxonomy was developed by Gershenson and Stauffer, as illustrated in Figure 3.7 [58]. It structures the business and product life cycle phase of a system in a hierarchical format. The taxonomy includes three levels of sub-taxons: *functional*, *task* and *attribute*. Figure 3.7 only presents the functional and task levels.

1 Marketing 1.1 Market investigation 1.2 Estimation of volume and price 1.3 Formation of market strategy 1.4 Develop Distribution system 1.5 Initiate Marketing 2 Business Environment 2.1 Societal 2.2. Industrial 2.3 Internal 3 Strategic Management 3.1 Environment scanning 3.2 Strategy formation 3.3 Strategy implementation 3.4 Evaluation and control 4 Finance 4.1 Description of organizational financial status 4.2 Financial analysis 4.3 Return on investment analysis 4.4 Capital formation 4.5 Profit performance evaluation 5 Accounting 5.1 Data for cost estimation 5.2 Productivity analysis 5.3 Feasibility of plan 5.4 Collect cost data	6 Manufacturing 6.1 Part production 6.2 Finishing 6.3 Joining 6.4 Top level assembly 6.5 Inspection/Quality assurance 7 Shipping 7.1 Packaging 7.2 Warehousing and handling 7.3 Transportation 8 Support & Service 8.1 Diagnostics 8.2 Maintenance 8.3 Repair 8.4 Customer Support 9 Retirement 9.1 Reuse 9.2 Product extension 9.3 Remanufacturing 9.4 Recycle 9.5 Disposition
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Figure 3.7: Corporate requirements taxonomy [58].

The *functional* level represents milestones actions that must be performed during the life cycle of the system. Each functional taxon regroups *tasks* that describe actions required to achieve higher level functions. The task sub-taxon can include many levels, and each of these levels should provide additional information about how to achieve the previous level task. For example the functional level ***Shipping*** requires the tasks *packaging*, *warehousing and handling*, and *transportation*. The third taxon not depicted in Figure 3.7, is the *attribute* taxon. Gershenson and Stauffer subdivide this sub-taxon into six attributes, which include geometry, feature, surface condition, tolerances, material and facilities. These attributes are manufacturing oriented, however one can imagine and create new attributes or even new sub-taxons to characterize the tasks at hand. This corporate taxonomy describes a top-down hierarchical approach starting with one element of the user context taxonomy, and decomposing the product and processes into functions, tasks and attributes.

Gershenson and Stauffer’s requirements corporate taxonomy is intended to be general, and consequently it can be applied to a large number of new projects regardless of the field of application. It represents a good foundation for the development of a new requirement taxonomy for complex aerospace systems. The rest of this section describes current systems engineer’s approaches to classify and manage requirements.

Taxonomy in Systems Engineering

From the systems engineering perspective, two requirements classification approaches are discussed in more detail. The first one from the INCOSE handbook, and the second one from the IEEE.

INCOSE does not define a specific requirements taxonomy, instead they suggest an iterative process of identifying, defining and refining requirements [82]. The process starts by describing sources of requirements, as illustrated in Figure 3.8. These sources of requirements are similar to the user context of Gershenson and Stauffer’s taxonomy. The INCOSE handbook defines environments instead of user-context: external, enterprise and project environment. Furthermore, it is recommended to define a database of “baseline systems requirements derived from the source” [82]. This initial set of requirements should be

“complete” and at the same time “minimum”. “Complete” so that all the major system level functions are taken into account, and “minimum” to reduce the confusion and uncertainty associated with a large number of requirements. This database should include the set of requirements listed in Table 3.3.

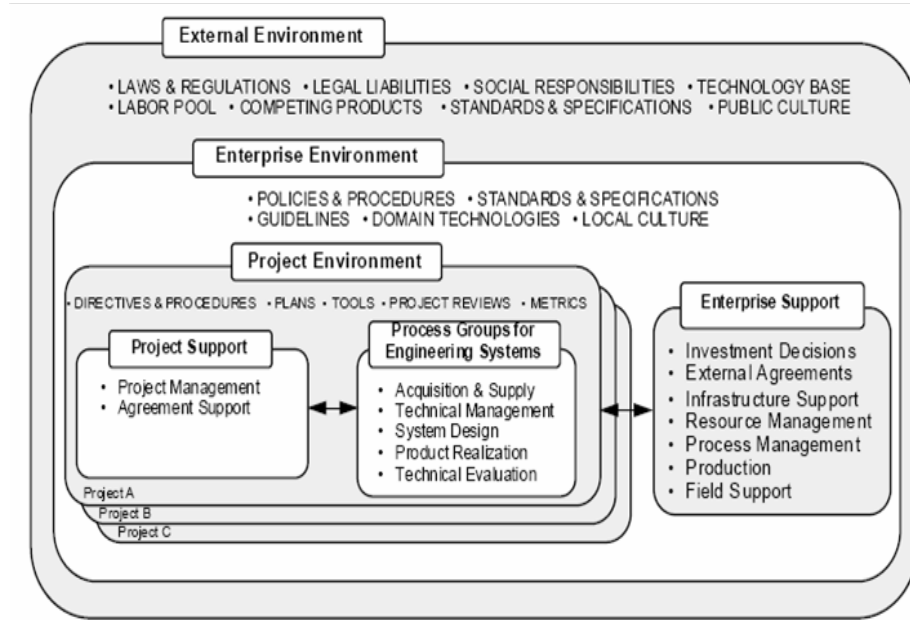


Figure 3.8: INCOSE - sources of requirements [82].

The types of requirements listed in Table 3.3 can be viewed as categories or taxons used to classify the requirements. Before this classification, requirements need to be defined following an iterative “top-down” and “bottom up” approach. The process starts by decomposing the system level requirements into lower level requirements (top-down). Once the requirements cannot be further decomposed, resources are allocated from lower level to higher level requirements up to the system level requirements (bottom-up). While performing this task, it is important to satisfy the traceability of requirements in order to have a continuous flow from high to low-level requirements.

The INCOSE handbook suggests baseline requirements and guidelines for the requirements elicitation process, however there is a need to also define a taxonomy structure or taxons. The taxons facilitate the classification of requirements by limiting the number of

Table 3.3: INCOSE - Baseline set of requirements [82].

Project requirements
Mission requirements
Customer specified constraints
Interface, environmental, and non-functional requirements
Unclear issues discovered in the requirement analysis process
An audit of the resolution of the issues raised
Verification methods required by the customer

categories which reduce uncertainty and confusion. This issue is covered in a system engineering paper published by White and Edwards in the IEEE literature.

White and Edwards specify a taxonomy for complex system requirements [192]. Their top-level taxonomy is divided in three views: stakeholder views, domain views, and capture views. First, the stakeholder views define requirements from the end-users, and requirements coming from any person involved in the system development life cycle. Second, the domain views are specific system requirements and consequently depend on the type of system. For example during the selection of a propulsion system, if the design team has a choice between an internal combustion engine with a propeller and a turbine engine, each of these systems are completely different; and therefore their system requirements are also very different. Third, the capture views represent what the system must achieve. It is one level of abstraction higher than the domain views. The capture views include operational environment, system capabilities, system constraints, development requirements, verification and validation requirements, and specification of system growth and change. The different taxons are illustrated in Figure 3.9.

This paragraph describes the major taxons presented in the requirements taxonomy of Figure 3.9. The *operational environment* includes all requirements related to the system deployment and interactions with other systems. The *system capabilities* describe the actions or missions performed by the system, while the *systems constraints* include any limit, intentional or not, imposed on the system capabilities. These three taxons are directly linked with the system, the next three are linked to processes surrounding the system. The *development requirements* supports the development process of the system, from planning

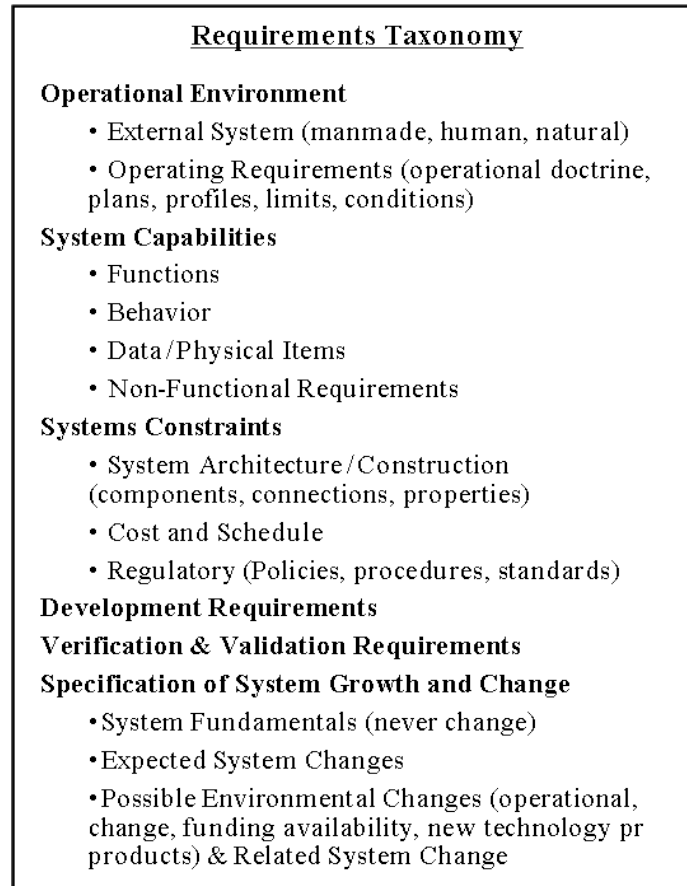


Figure 3.9: Capture views - requirements taxonomy [192].

and management, to operations. The *verification and validation requirements* specify requirements needed to test and validate the system with respect to the initial operational, capability and constraint requirements. The last taxon includes the *specification of system growth and change*. Since this taxonomy is meant for complex systems, which have a long life cycle, it is important to take into account the evolution of the requirements in time. Accounting for these requirements adds flexibility to the system, and it facilitates the potential integration of new technologies to the system.

The requirement taxonomy established by White and Edwards also starts from a higher level perspective by establishing top-level views: stakeholder, domain, and capture. The authors then describe the multiple levels of the capture views. As mentioned in their future works section, the current requirement taxonomy needs to be refined to include relationships between the different views: stakeholder, domain and capture. Furthermore, to meet the

completeness property of taxonomy, the taxons should be created so that they include all the requirement types of section 3.1.2.

The existing taxonomies presented in this section provide valuable information about the systems requirements. However none of these taxonomies can be implemented directly with the proposed methodology. Consequently, there is a need to create a new taxonomy that would represent the foundation of the requirements methodology. The development of this taxonomy is described in Chapter 4.

3.3 *Requirements Mapping*

This section on the requirements mapping is intended to explore the literature regarding the first two research questions:

RQ1: How to classify the requirements with respect to stakeholders, functions and systems?

RQ2: How to combine the function and systems hierarchies in the mapping?

In addition to these two research questions, the requirements mapping also refers to the type of information included in the methodology. Early in the conceptual design more qualitative information is used to describe and define the systems. As the project progresses, the definition of the problem becomes crisper and more quantitative information is used to define the problem. This section describes both approaches starting with the mapping of qualitative information and going into the mapping of quantitative information. In this research quantitative data implies a numerical form whereas qualitative information can be based on words, even though these words can be converted into a numerical form [176].

Qualitative relationships are usually subjective, and the goodness of the mapping generally depends on the level of knowledge and experience of the decision makers. An example of qualitative mapping would be to create relationships based on an interval scale of *weak*, *medium* and *strong* relationships, as illustrated in Figure 3.10. A sample of qualitative mapping technique includes the GOTChA approach, the Quality Function Deployment process (QFD), the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP). As it will be further emphasized in this section, QFD, AHP and ANP can also be used with

quantitative information.

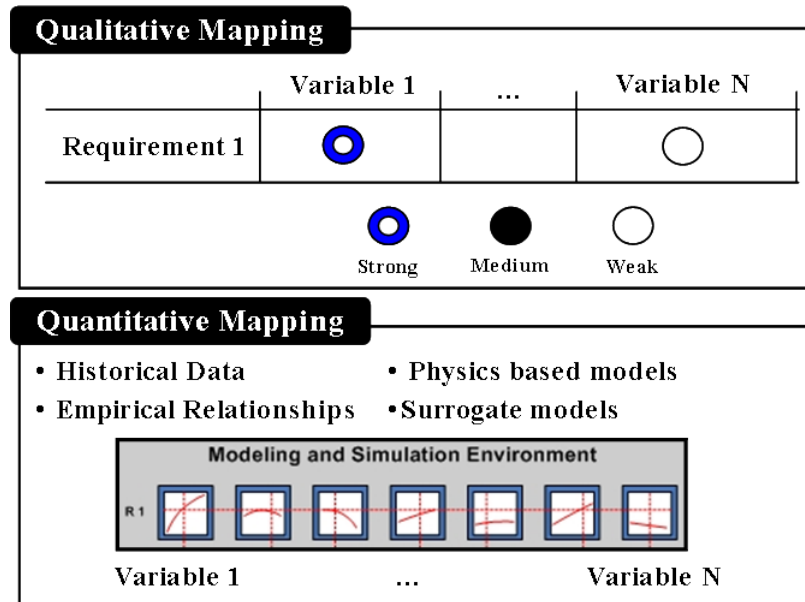


Figure 3.10: Example of qualitative and quantitative mapping.

In contrast, quantitative relationships refer to a numerical scale, which can include continuous or ratio scales. In Figure 3.10, examples of quantitative mapping include historical data, empirical relationships, physics-based models, and surrogate models. This figure shows the quantitative relationships between one response and N design variables. Each plot represents the variation of the response for a specific range of design variables. Looking at the slopes and shapes of these curves provides interesting quantitative information for the design team and decision makers. The Unified Trade-off environment is an example of quantitative mapping methodology, it is discussed in section 3.3.5.

This section reviews five tools and processes that have the potential of providing a structured framework while assuring the traceability between the stakeholder expectations and systems alternatives. The five approaches are listed as follows:

- Requirements Mapping Techniques
 - I. Decision Model - GOTChA Chart
 - II. Quality Function Deployment process
 - III. Analytic Hierarchy Process
 - IV. Analytic Network Process

V. Unified Trade-Off environment

While describing these techniques, it is important to estimate their relevance with respect to this work's research areas and proposed methodology. To do so the following criteria have been defined to compare the advantages and disadvantages of the tools.

- Scalable to complex systems
 - (1) Allow a structured decomposition of the systems and operational characteristics;
 - (2) Provide a common framework for the proposed methodology to minimize the number of tools and processes (simplicity);
- Provide a framework to define the requirements
 - (3) Traceability from expectations to systems alternatives;
 - (4) Allow the use of both qualitative and quantitative information;
- Provide a framework to down-select the requirements
 - (5) Assist the user to define the relative importance of the expectations, requirements and systems;
- Provide a framework to perform uncertainty analysis
 - (6) Uncertainty on the stakeholders preferences, which influence the importance of the requirements and ultimately the customer satisfaction;
 - (7) Manage the acquired information.

The importance of a common framework, criteria (2), may not have been emphasized as much as the other criteria in chapters 1 and 2. This specific criteria originates from the following quote from the INCOSE handbook [83]:

“ Big gains could be made by focusing on the most important customers needs and using a select group of synergistic system engineering tools/practices.”

The application of the proposed methodology by the community will depend on if it provides more insight to the design problem than current methodologies, while being easier to use.

3.3.1 Goals, Objectives, Technical Challenges and Approaches (GOTChA)

The GOTChA process creates a mapping between the project goals (inputs) and approaches (outputs) identified to achieve these goals. The GOTChA process has been applied by the Department of Defense to create technology portfolios [147]. Also the NASA Vehicle Systems Program team used GOTChA charts to assess vehicles capabilities while tying together technological goals and technology investments [33]; an example of a GOTChA chart is illustrated in Figure 3.11.

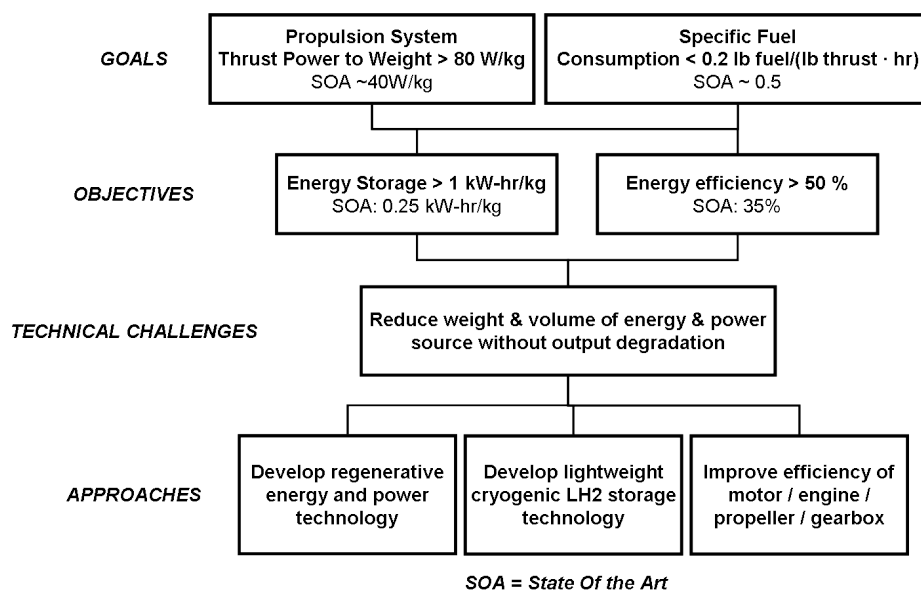


Figure 3.11: GOTChA Chart: Example of UAV power and propulsion capability assessment (modified from [33]).

This exploratory process includes information gathering and brainstorming exercises. In the example of Figure 3.11, the goals represent systems measures of effectiveness, which includes state-of-the-art values as reference. The second level defines the objectives required to achieve the goals. The objectives also include threshold measures of effectiveness and state-of-the-art values. The third level of the chart lists technical challenges that constraint the achievement of the goals and objectives. The technical challenges emphasize how specific engineering characteristics should be modified with respect to the higher level objectives. Finally, a series of approaches are defined to carry the development of the goals and objectives while taking into account the technical challenges.

The GOTChA chart is meant to structure and summarize the information gathered during the problem definition. Table 3.4 enumerates the advantages and disadvantages of the GOTChA process with respect to the requirements mapping criteria.

Table 3.4: Advantages and disadvantages of GOTChA.

Advantages	Disadvantages
Clear traceability between goals (expectations) and approaches (systems alternatives)	No comparison capability between the elements of the model
Reference the goals and objectives with respect to the SOA (benchmarking)	Cannot be used directly for requirements down-selection
Include a hierarchical structure between goals and objectives	No uncertainty analysis capability
Enumerate important criteria for down-selection through the technical challenges	

Figure 3.12 translates these advantages and disadvantages into a qualitative comparison that is used at the end of this chapter to summarize how the concepts embedded in the GOTChA process can be used to help the development of the proposed methodology.

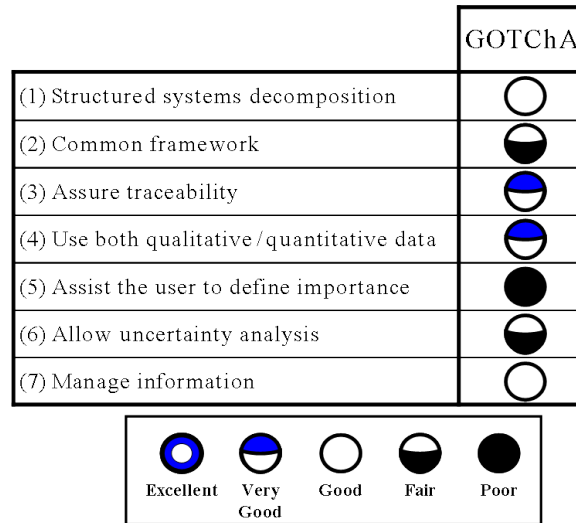


Figure 3.12: GOTChA qualitative comparison with respect to methodology criteria.

3.3.2 Quality Function Deployment

The Quality Function Deployment process was developed in Japan during the 1970s with the objective of designing quality products by translating the customer desires into engineering characteristics [4]. According to Sullivan [166] the QFD process can be defined as “... *a system to assure that customer needs drive the product design and production process.*”

The popularity of the QFD process is due to its capacity to (1) reduce the ambiguity surrounding the customer desires, (2) increase the effectiveness of the product development and (3) improve communication and teamwork [45, 25, 77]. As a result, it has been asserted that the QFD process reduces the number of design changes, as notionally depicted in Figure 3.13[65].

Japanese automaker with QFD made fewer changes than U.S. company without QFD

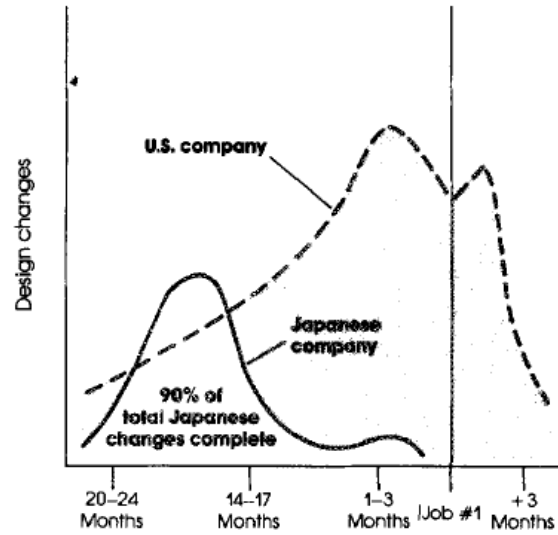


Figure 3.13: Design Changes vs. Time[65]

Early design changes represent important cost saving and significant reduction of the design cycle time, which has a great impact on the initial market share of the new product. The main purpose of this approach is to guide the design team through their decision process, with the objective of creating quality products. This section describes the QFD process, and more specifically the House of Quality (HoQ) which corresponds to the first phase of the process, Figure 3.14.

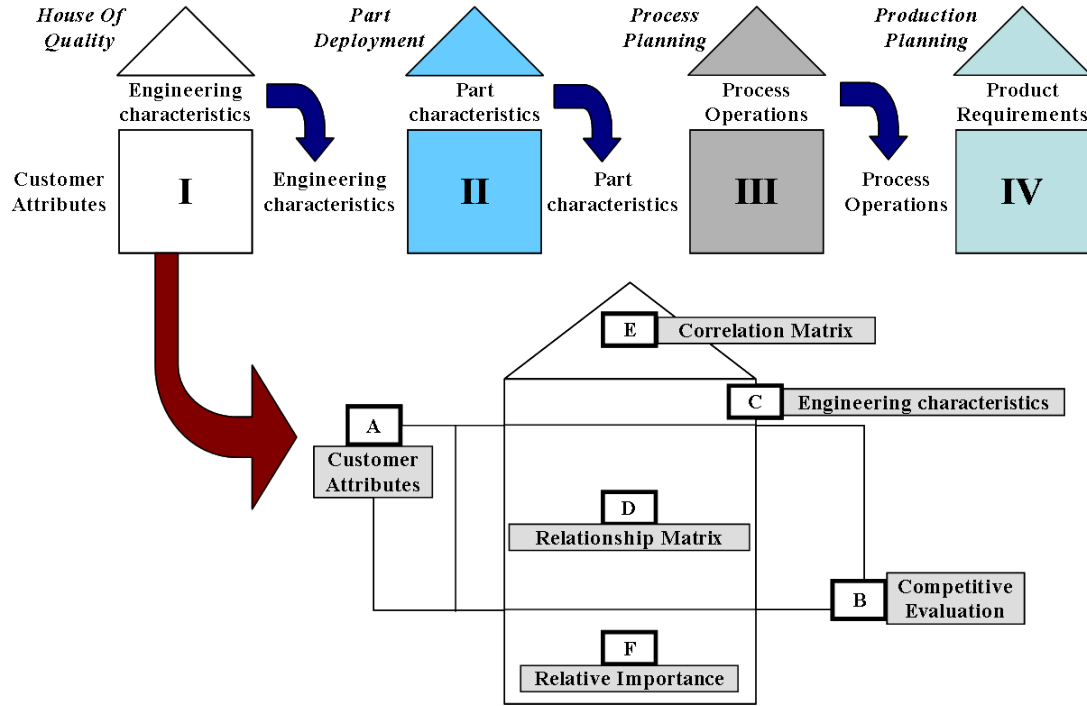


Figure 3.14: Quality Function Deployment Process (modified from [45, 25]).

The House of Quality starts with a list of customer attributes (*Whats*) and engineering characteristics (*How's*). First, (Figure 3.14- Step A) the design team assigns relative weights to the customer requirements. Second, (Step B) information is gathered from competing products and historical data for benchmarking. This information can also be used to identify or refine the list of engineering characteristics (Step C). The relationship matrix (Step D) is populated using a nonlinear scale $\{0, 1, 3, 9\}$ to determine the impact of engineering characteristics on the customer requirements. The correlation matrix (Step E), also called the “roof of the house”, is used to identify cooperative or trade-off relationships between the engineering characteristics. The relationships are qualified as strong, medium or weak positive (cooperative), or negative (trade-off) relationships. The creation of the relationship and correlation matrices is the core activity of the QFD process. Based on the relationships matrix and the relative importance assigned to the customer attributes, the relative importance of the engineering characteristics (Step F) can be evaluated using a weighted sum (Eq. 3.1).

$$EC_j = \sum_{i=1}^N w_i R_{ij} \quad (3.1)$$

Where w_i represents the importance assigned to the customer attributes (i) and R_{ij} represents the relationship value $\{0, 1, 3, 9\}$ between the customer attribute i and the engineering characteristic (j). The relative importance of the engineering characteristics can then be compared with the information gathered in the competitive benchmarking. Consequently one can identify how to improve an existing product or design a new product by focusing on the most important engineering characteristics, and ultimately satisfying the majority if not all of the customer attributes.

The Quality Function Deployment process has been applied in many fields, and extensive research has been performed on different applications of the process such as customer analysis, product design, decision making, strategic planning, etc. In 2002, Chan et Wu published a detailed literature review on the QFD process involving more than 600 QFD publications [26]. For the development of the proposed methodology, more than 40 QFD publications have been investigated, with emphasis on requirements definitions, product design and decision making. Table 3.5 lists 12 papers that are aligned with the scope of this research.

The publications of Table 3.5 provide important insight regarding the use of the QFD process. In the survey performed by Cristiano et al. with more than 400 U.S. and Japanese companies, the majority of companies estimated that the use of QFD resulted in better designs, improved communication, and corporate memory [34]. Since the definition of a better design is relative to the level of customer satisfaction, Kamara et al. [87] and Lai et al. [97] analyzed different approaches to assess the customer satisfaction with methods integrated to the QFD.

As the product becomes more complex, other techniques are combined with the QFD process to assist the user in their understanding of the problem. For instance, AHP is frequently used to prioritize the importance of the customer attributes [77], while Neural Networks and Response Surface Methods are used to fill the relationship matrix with data gathered from the benchmarking [205, 22, 163].

Table 3.5: Summary of the QFD literature review.

Research Area	Ref.	Year	Author	Objective
Define Requirements	[34]	2000	Cristiano et al. (2000)	Survey more than 400 companies in U.S.A and Japan on their use of QFD
	[87]	2000	Kamara et al. (2000)	Utilize QFD process for the processing of clients requirements
	[97]	2004	Lai et al. (2004)	Combine the Kano Model with the QFD to meet the customer requirements
Product Design	[141]	1998	Park et al. (1998)	Select optimal set of engineering characteristics combining QFD and MADM* technique
	[77]	2002	Hsiao (2002)	Improve product quality by combining QFD, FMEA*, DFA* & AHP
Decision Model <i>Resource allocation</i>	[205]	1996	Zhang et al. (1996)	Fill the QFD relationships matrix by using Neural Networks by learning from examples
	[22]	2000	Bouchereau et al. (2000)	Discuss the use of Fuzzy Logic, Artificial Neural Networks and the Taguchi method
	[163]	2002	Yang et al. (2002)	Optimize customer satisfaction by varying the engineering characteristics with RSM*
	[19]	1998	Bode et al. (1998)	Include the product resources in the QFD process
	[54, 55, 56]	1998, 2002, 2003	Fung et al. (1998, 2002, 2003)	Allocate resources to engineering to maximize the customer satisfaction

* **MADM**: Multi-Attribute Decision Method

* **RSM**: Response Surface Method








* **FMEA**: Failure Mode and Effects Analysis

* **DFA**: Design For Assembly

To summarize the literature survey, Figure 3.15 illustrates the relationships between the QFD process and the desired criteria of the proposed methodology.

With respect to the requirements mapping, the QFD process is a good common framework. It enables the mapping between customer requirements and engineering characteristics, and at the same time assures the traceability and management of information. It uses both qualitative information, from the user, and quantitative data for the benchmarking analysis. However the QFD by itself does not take into account the uncertainty associated with the weights and relationships included in the matrices [187, 66].

Even though the QFD process provides an initial systems decomposition, additional improvement can be made in that area. According to Wasserman, QFD benefits could be enhanced by using hierarchical arrangement of the QFD matrices to differentiate between

	QFD
(1) Structured systems decomposition	
(2) Common framework	
(3) Assure traceability	
(4) Use both qualitative /quantitative data	
(5) Assist the user to define importance	
(6) Allow uncertainty analysis	
(7) Manage information	






				
Excellent	Very Good	Good	Fair	Poor

Figure 3.15: Qualitative Comparison of QFD with respect to mapping criteria.

the various levels of requirements [191]. Kamara et al. also emphasized that the hierarchical decomposition of requirements (from general to specific) improves the understanding and traceability of requirements [87]. A tool identified to perform a hierarchical system decomposition is the Analytic Hierarchy Process, which is discussed in the next section.

3.3.3 Analytic Hierarchy Process

The Analytic Hierarchy Process has been developed by Thomas L. Saaty as a mathematical process to capture individual or group preferences by using a hierarchical structure [156]. A hierarchical structure is based on a tree diagram that structures the complexity of a problem into multiple levels; assuming that a component of a higher level can be decomposed into multiple elements at lower levels. The decomposition process is often referred to as Top-Down (from higher to lower levels), while the synthesis process is referred to as Bottom-Up (from lower to higher levels). The Analytic Hierarchy Process uses the hierarchical structure to frame the problem by starting at the top with an overarching goal and then defining the lower levels in terms of sub-goals, criteria, and alternatives. Figure 3.16 illustrates the activities performed in AHP with a notional example of hierarchy.

The first step of AHP is to create the hierarchical model (Figure 3.16 Step 1) , which results from a brainstorming activity, followed by the creation of an affinity diagram to categorize the identified elements [82]. Once the components are organized within the various

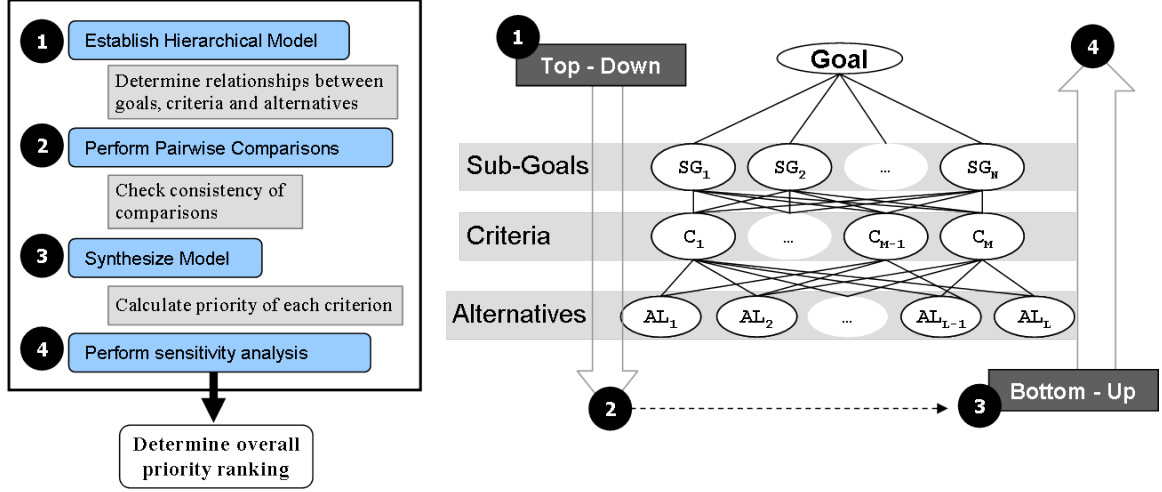


Figure 3.16: Flowchart of the Analytic Hierarchy Process.

levels of the hierarchy, the next step is to perform the pairwise comparisons (Figure 3.16 Step 2).

The pairwise comparisons are based on a ratio scale [63, 108, 157, 51]. According to Saaty in “The Seven Pillars of the Analytic Hierarchy Process”, the use of ratio scale is fundamental component to the synthesis of priorities of a hierarchical model because [108]:

- I. ratio scale measurement can be combined with customized scales;
- II. ratio scale allows the generalization of a decision theory in the presence of dependence and feedback, because they can be added and multiplied;
- III. ratio scale can be used in a framework involving several hierarchies.

Consequently, in the presence of both qualitative and quantitative information, ratio scale allows the relative comparison of physical characteristics (area, volume, mass, etc.) as well as subjective characteristics (risk, safety, etc.).

To compare the various elements of a hierarchical structure, Saaty developed a fundamental ratio scale based on the mathematics of neural firing [157] as illustrated in Figure 3.17. The pairwise comparison concept originates from an experienced performed by Weber in 1846. Weber was trying to quantify the “*perception of change*” by comparing different masses, two at the time, one per hand. This experience led to the formulation of Weber’s law, which states that “*change in sensation is noticed when the stimulus is increased by a*

constant percentage of the stimulus itself” [157]. Based on this notion of stimulus, Saaty created a nine point scale, which he justifies as follows [157]:

“Qualitatively, people have a capacity to divide their response to stimuli into three categories: high, medium and low. They also have the capacity to refine this division by further subdividing each of these intensities of responses into high, medium and low, thus yielding in all nine subdivisions.”

Low			Medium			Large		
1	2	3	4	5	6	7	8	9
Intensity of importance	Definition					Explanation		
1	Equal importance					Two activities contribute equally to the objective		
2	Weak							
3	Moderate importance					Experience and judgment slightly favor one activity over another		
4	Moderate plus							
5	Strong importance					Experience and judgment strongly favor one activity over another		
6	Strong plus							
7	Very strong or demonstrated importance					An activity is favored very strongly over another; its dominance demonstrated in practice		
8	Very, very strong							
9	Extreme importance					The evidence favoring one activity over another is of the highest possible order of affirmation		
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i					A reasonable assumption		

Figure 3.17: AHP fundamental scale [157].

In Figure 3.17, the reciprocal implies that if A is judged twice as important as B ($A = 2*B$), then B is half as important as A ($B = 0.5*A$). The results of the pairwise comparisons are stored in a matrix, the comparison matrix. A comparison matrix can be generalized in the matrix where $A = (a_{ij})$ as depicted in Eq. 3.2.

$$Aw = nw \Rightarrow \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} \quad (3.2)$$

Where $a_{ij} = w_i/w_j$. The matrix A is said to be reciprocal if $a_{ji} = 1/a_{ij}$ for all $i, j = 1, 2, \dots, n$; implying that $a_{ii} = 1$ for all values of i . Also matrix A is said to be consistent if $a_{ij}a_{jk} = a_{ik}$ for all $i, j, k = 1, 2, \dots, n$. Note that the equations used to explain the derivation of the priorities and consistency of the pairwise comparisons are taken from Reference [157].

More information about the development of the mathematical model can also be found in the same reference.

To illustrate the concept of comparison matrix and consistency, Figure 3.18 shows an example application of AHP in which the user has to determine the relative area of various geometrical shapes; this example is taken from reference [159].

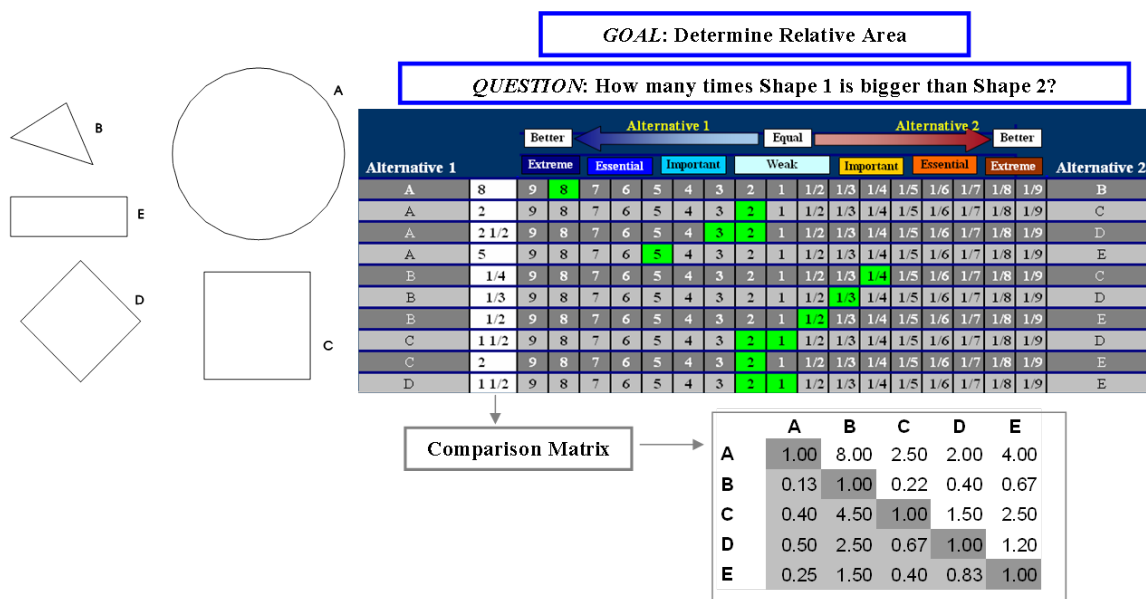


Figure 3.18: AHP example: Determine the relative area of various shapes.

When the pairwise comparisons of the areas are completed, the next step is to solve the matrix system to find the relative area. In most decision making problems, the matrix system is solved to evaluate the priorities (weights) or relative importance of different criteria.

The evaluation of the priorities from the comparison matrix is performed through an eigenvalue formulation. If the matrix A is not consistent, then the priorities are solved with $Aw = \lambda_{max}w$, where λ_{max} is the principal eigenvalue of A . It has been shown that to maintain reasonable consistency when deriving priorities from pairwise comparisons, the number of factors (n) being considered must be less or equal to nine [157]. In AHP the consistency of the priorities is assessed using a consistency ratio (C.R.), consistency index (C.I.) and a random consistency index (R.I.) as depicted in Eq. 3.3.

$$C.I. = \frac{\lambda_{max} - n}{n-1} \quad (3.3)$$

$$C.R. = \frac{C.I.}{R.I.}$$

Where n represents the number of elements in the matrix. The random consistency index is an average value derived from a large sample of reciprocal matrices having the n elements varying from 1/9 to 9. Table 3.6 lists the R.I. for up to ten elements.

Table 3.6: Random consistency index for different matrix [157].

n	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

It is suggested that the comparison matrix should be accepted if the C.R. is smaller than 0.1; it is also stated that a value of 0.2 can be tolerated [157]. To evaluate the C.I., Saaty proves in Theorem 2-5 of Reference [157] that the compatibility index (S.I.) can be used to calculate the principal eigenvalue of the comparison matrix, as derived in Eq. 3.4.

Let $W = (w_i/w_j)$, where $w = (w_1, \dots, w_n)$

Theorem 2-5: $\frac{1}{n^2} e^T A \circ W^T e = \frac{\lambda_{max}}{n} = S.I.$

Proof : From $Aw = \lambda_{max}w$, we have (3.4)

$$\sum_{j=1}^n a_{ij} w_j = \lambda_{max} w_i \text{ and}$$

$$\frac{1}{n^2} e^T A \circ W^T e = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n a_{ij} \frac{w_j}{w_i} = \frac{\lambda_{max}}{n}$$

Consequently if one knows the principal eigenvalue, λ_{max} , it is possible to calculate the S.I, C.I, and C.R. For the relative area example of Figure 3.18, the results of the eigenvalue problem with the consistency and compatibility indexes are shown in Figure 3.19.

	Actual Relative Area	From Matrix A	Infinite Norm	λ_{max}	C.I.	S.I	R.I.	C.R.
A	0.470	0.453	1.000	5.0099	0.0025	1.0020	1.1100	0.0022
B	0.050	0.055	0.121					
C	0.240	0.224	0.495					
D	0.150	0.163	0.359					
E	0.100	0.105	0.231					

Figure 3.19: Results of the area comparison using AHP.

From Figure 3.19, it can be seen that the consistency ratio is well below the recommended

threshold of 0.1. This could also have been deduced by looking at the maximum eigenvalue being very close to the number of elements in the matrix. Consequently the consistency index (C.I.) is small and the compatibility index (S.I.) tends toward 1. Furthermore, Figure 3.19 compares the actual normalized relative areas and the results from the eigenvalue solution of the comparison matrix. This example has been proven effective to demonstrate the capability of AHP, **it shows that even without measurement one can provide an accurate estimation of the relative areas**. Therefore assuming that the area of the circle A is known, one can normalize (*infinite norm*) the resulting relative areas using the circle area to determine all the other areas.

3.3.3.1 Applications of the Analytic Hierarchy Process

Since its development AHP has been widely used in many applications. A survey by Steuer et al. (2003) emphasized the use of AHP in finance by referring to 18 publications[164]. Vaidya et al. (2006) published a literature survey including 150 publications describing the applications of AHP to: selection process, evaluation process, Benefit-Costs analysis, allocation process, planning and development, forecasting, and AHP integrated with the QFD process[183]. Due to the emergence of analytical tools combined with AHP, Ho (2007) published a literature survey including 66 publications on the integration of AHP with: mathematical programming techniques, QFD, meta-heuristics approaches, SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), and Data Envelopment Analysis (DEA) [75].

For the current research, more than 50 AHP publications have been reviewed in the areas of priority and ranking, selection process, allocation process, and integration of AHP with QFD. Table 3.7 lists a summary of the publications that analyze the applications of AHP in terms of priority and ranking, the selection process, and the allocation process. It is to be noted that in this work, the benefits-costs analysis are considered part of the selection process. This topic will be described in more details in section 3.5.

Important insights can be inferred from the literature review of Table 3.7. Fundamentally, AHP provides an efficient and mathematically proven approach to evaluate the priority

Table 3.7: Summary of AHP applications literature review.

Research Area	Ref.	Year	Author	Objective
Priority and Ranking	[150]	1997	Rosenbloom	Treat pairwise comparison as random variable with Monte-Carlo Simulation
	[198]	2001	Yeh et al.	A consensus approach to synthesize the decision-makers judgments
	[10]	2006	Aull-Hyde et al.	Explore the consistency of various AHP aggregation methods
	[112]	2007	Mamat et al.	Evaluation of rank consistency and time to perform pairwise comparison
Selection Process	[23]	2001	Cagno et al.	Use AHP to evaluate the probability of winning a bidding process (Monte-Carlo)
	[194]	2003	Winebrake et al.	Apply AHP to a perspective-based scenario analysis
	[16]	2006	Bertolini et al.	Combine AHP & Goal programming in selection problem
	[185]	2007	Van de Water	Build an AHP decision model to “make” or “buy” a product
	[27]	2007	Chang et al.	Application of AHP to select the best alternative
Allocation Process	[159]	2003	Saaty et al.	Allocation of intangible resources (i.e., product quality)
	[158]	2007	Saaty et al.	Application of AHP in human resource allocation in terms of employee and salary
	[78]	2008	Hsu et al.	Apply AHP to optimize the resource allocation to ensure a competitive advantage

of goals, criteria, and alternatives based on the preferences of the decision makers. By analyzing the range of applications, one can conclude that AHP is a flexible tool that can be adapted to a large number of decision making problems. This flexibility of AHP also allows for its integration with other tools like linear or goal programming to enhance the selection and allocation processes.

The Analytic Hierarchy Process has many strengths. The hierarchical structure of the goals, criteria, and alternatives provides a logical structure for the selection process. The hierarchical model enables the visualization of the traceability between the various components of the hierarchy, and the storage of information. The traceability characteristic of AHP makes it possible to perform sensitivity analysis at every level of the hierarchy. Performing these analyses provide more information to the decision makers and consequently reduces the uncertainty surrounding the project. Another way to reduce the uncertainty in AHP is

to verify the consistency of the pairwise comparisons with the consistency ratio. Also, as it is the case for the QFD, increasing the interactions between team members throughout the process improves the communication and teamwork. Finally, specifically for a resource allocation process, AHP has been used with both tangible (i.e., money) and intangible (i.e., quality, complexity) resources. In other words, AHP can be used with both qualitative and quantitative information, which is an important criterion for the proposed methodology.

The second part of the literature review is about the integration of the AHP with the QFD process. In this context, AHP has been used prior to the QFD to determine the priorities of the customer requirements. Also, it has been used inside the QFD process to compare the alternatives of the competitive evaluation, and it has been applied post QFD to down-select the product alternatives. Table 3.8 lists the publications in which both AHP & QFD have been combined together.

Table 3.8: Literature Review of AHP and QFD.

Research Area	Ref.	Year	Author	Objective
Requirements Definition	[110]	2002	Madu et al.	Prioritize customer requirements before the QFD
	[9]	1994	Armancost et al.	Apply QFD and AHP to identify and prioritize customer requirements
	[189]	1998	Wang et al.	Apply AHP to both customer requirements and relationship matrix of the QFD
	[95]	2002	Kwong et al.	Combining fuzzy set theory & AHP to determine the importance of customer requirements
	[96]	2003	Kwong et al.	Determining the importance of customer requirements with fuzzy AHP
	[128]	2003	Myint	Use AHP and Neural Networks with the QFD process
Down-Selection	[77]	2002	Hsiao	AHP used to in the down-selection of the product alternatives






The integration of AHP with QFD extends the traceability of information from the customer requirements to the down-selection of product alternatives.

By itself, the QFD process takes as inputs a fixed set of customer requirements. The information gathered to select this set of requirements is often not included in the process. Furthermore the problem definition is often ambiguous and lacks structure since the decision makers have to select requirements facing incomplete knowledge and a large number of possibilities. This is an area in which AHP can structure the information by using its

hierarchical model toward the selection of requirements.

To summarize this section, Figure 3.20 compares the strengths and weaknesses of AHP with respect to the requirements mapping criteria.

	AHP
(1) Structured systems decomposition	
(2) Common framework	
(3) Assure traceability	
(4) Use both qualitative /quantitative data	
(5) Assist the user to define importance	
(6) Allow uncertainty analysis	
(7) Manage information	

Excellent
Very Good
Good
Fair
Poor

Figure 3.20: AHP qualitative comparison with respect to mapping criteria.

3.3.4 Analytic Network Process

The Analytic Network Process (ANP) is a generalization of the Analytic Hierarchy Process. The difference between AHP and ANP lies in the structure of the information. The previous section discussed that AHP is based on a unidirectional hierarchy structuring the problem in multiple levels. In this case unidirectional implies that only higher level components influenced lower level components of the hierarchy. The structure of ANP is more flexible and allows for inter-dependencies between components at the same or different levels of the hierarchy. Saaty refers to this type of structure as feedback systems [157]. An example of feedback networks is presented in Figure 3.21.

From Figure 3.21 it can be seen that the network is composed of four components C1 to C4. Each component includes either a hierarchy or another network. In this example component C2 is exploded into a hierarchy with a feedback loop, assuming that Alternative(3) influences Alternative(2). In his book on ANP, Saaty describes in detail the different types of networks and hierarchies [157].

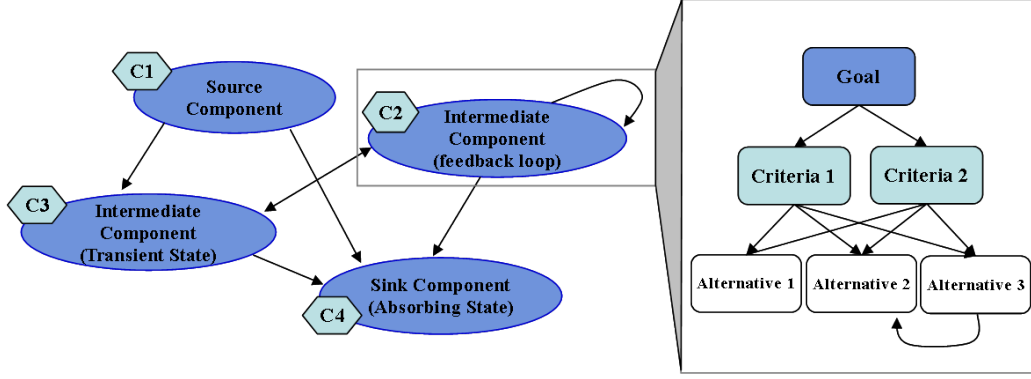


Figure 3.21: Example of feedback network (inspired from [157]).

Another distinction between AHP and ANP lies in the approach used to store the pairwise comparisons. In AHP the comparison matrix is sufficient to capture all the information, however in ANP the results of the comparisons are stored in a *supermatrix*. The supermatrix is used to store all the comparisons while taking into account the relationships and interdependence between the hierarchies and networks. The supermatrix corresponding to the example network of Figure 3.21 is depicted in the following matrix.

$$W = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & I & W_{23} & 0 \\ W_{31} & W_{32} & 0 & 0 \\ W_{41} & W_{42} & W_{43} & I \end{bmatrix}$$

A component of the supermatrix like W_{23} is called a block matrix and has the following form [157].

$$W_{ij} = \begin{bmatrix} w_{i_1j_1} & w_{i_1j_2} & \cdots & w_{i_1jn_j} \\ w_{i_2j_1} & w_{i_2j_2} & \cdots & w_{i_2jn_j} \\ \vdots & \vdots & \vdots & \vdots \\ w_{i_{n_i}j_1} & w_{i_{n_i}j_2} & \cdots & w_{i_{n_i}jn_j} \end{bmatrix}$$

The columns of the block matrix correspond to the principal eigenvector representing the importance of elements in the i th network component to elements of the j th network component. To derive the priority of the elements from the supermatrix one must ensure that every column of the matrix sums to unity, corresponding to a stochastic matrix. Saaty

states that “if the matrix is stochastic, the limit priorities can be viewed in a way to depend on the concepts of reducibility, primitivity, and cyclicity of the matrix” [157]. In reference [157], Saaty demonstrates that the priority of the elements in the supermatrix can be obtained by taking the limit of the matrix as its power tends toward infinity, a technique also known as the Cesaro sum, as given in Eq. 3.5.

$$\lim_{k \rightarrow \infty} (1/N) \sum_{k=1}^N W^k \quad (3.5)$$

Saaty explores the convergence characteristic of Eq. 3.5 in reference [157]. The fundamental idea of taking the limit of the matrix is to capture the influence of each element on every other element by multiplying them together. A notional example illustrating this concept is depicted as follows [157]:

$$W = \begin{bmatrix} 0 & W_{12} & 0 \\ 0 & 0 & W_{23} \\ W_{31} & 0 & 0 \end{bmatrix}; \quad W^2 = \begin{bmatrix} 0 & 0 & W_{12}W_{23} \\ W_{23}W_{31} & 0 & 0 \\ 0 & W_{31}W_{12} & 0 \end{bmatrix};$$

$$W^3 = \begin{bmatrix} W_{12}W_{23}W_{31} & 0 & 0 \\ 0 & W_{23}W_{31}W_{12} & 0 \\ 0 & 0 & W_{31}W_{12}W_{23} \end{bmatrix};$$

The results of Eq. 3.5 is often referred to as the limit matrix. The literature on the application of ANP is not as exhaustive as for AHP. Table 3.9 lists a summary of ANP publications applied to selection and ranking processes.

Most applications requiring the use of ANP are all based on feedback systems involving interdependencies between the criteria and/or alternatives. The two papers combining ANP & QFD in Table 3.9 are of a particular interest in this research. By its construction, the House of Quality in the QFD process includes matrices to evaluate interdependencies of customer requirements and engineering characteristics. Karsak et al. (2003) and Partovi (2007) took advantage of this fact to integrate ANP with the House of Quality. Two main advantages can be inferred from these publications, (1) ANP is better adapted to the QFD decomposition process; (2) the integrated ANP/QFD provides a framework allowing the use

Table 3.9: Summary of ANP applications literature review.

Research Area	Ref.	Year	Author	Objectives
Selection	[109]	1999	Meade et al.	Analyze how project alternatives impact business processes
	[121]	2002	Meade et al.	Competing R&D project selection
Ranking	[201]	2003	Yurdakul	Use ANP to measure the performance of manufacturing firm
Integrated ANP	[100]	2000	Lee et al.	Combine ANP and goal programming for system projects selection
	[91]	2003	Karsak et al.	Product planning using ANP, QFD and goal programming
	[174]	2005	Tesfamariam et al.	Combine systems dynamics and ANP applied to manufacturing
	[142]	2007	Partovi	Integrate ANP & QFD for process selection

of quantitative information in the decision process [91, 142]. Consequently, with respect to the criteria of the proposed methodology, ANP provides better decomposition and traceability than AHP. The overall qualitative comparison of ANP with the methodology criteria is illustrated in Figure 3.22.

	ANP
(1) Structured systems decomposition	
(2) Common framework	
(3) Assure traceability	
(4) Use both qualitative /quantitative data	
(5) Assist the user to define importance	
(6) Allow uncertainty analysis	
(7) Manage information	

Excellent	Very Good	Good	Fair	Poor

Figure 3.22: ANP qualitative comparison with respect to mapping criteria.

3.3.5 Unified Tradeoff Environment

In terms of requirements mapping, the tools described in the previous sections were based either on qualitative information (GOTChA) or a mix of qualitative and quantitative information (AHP, ANP). This section presents a requirement mapping technique purely based

on quantitative information.

The Unified Tradeoff Environment (UTE), created by Baker (2002) [11], enables the simultaneous assessment of requirements, design and technology variables. The motivation behind this tool is to create the “*ability to capture the complex design space with a mathematical model that equates the system level attributes of the complex system to various factors (requirements, design variables and technologies)*”[12]. Complex systems are characterized by many interactions which can be trivial or non-trivial, linear or highly non-linear. UTE allows the visualization of these interactions, as shown in Figure 3.23. The mathematical model used by Baker is based on Response Surface Methodology (RSM) [127], however other types of metamodeling techniques could be used to obtain the UTE framework.

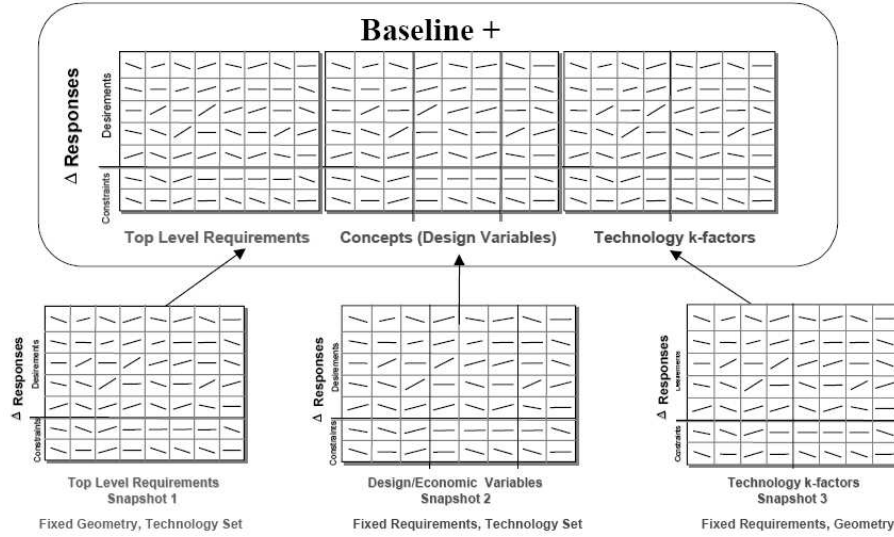


Figure 3.23: Unified Trade off Environment[11]

The Unified Tradeoff Environment process takes as inputs a set of requirements, coming either from the QFD process or directly from a request for proposal. Each requirement needs to be modeled mathematically based on a set of design variables. The models used in UTE can be physics-based models or obtained from empirical relationships. To accelerate the process these models are often approximated using surrogate models [39], which can then be combined in a unique environment.

For the requirements analysis process, UTE analyzes the impact of varying design and technology variables on a set of pre-defined requirements. If the design team wants to

integrate other requirements, new surrogate models have to be created and integrated to the environment. In this perspective UTE is not very flexible. Furthermore, the set of requirements is not directly mapped to the requirements definition process (i.e., QFD), and consequently the importance of the requirements with respect to the preference of the stakeholders is not taken into account in UTE.

It has been emphasized in the literature that without a direct mapping between requirements definition and the requirements model, it is difficult to capture the dynamic behavior of the customers [101]. Creating a mapping between the requirement definition process and UTE is a difficult task, since UTE only takes as inputs quantitative data whereas the requirements definition process includes both qualitative and quantitative information. Consequently, the lack of flexibility of UTE suggests that the method is mostly applicable to well-defined conceptual design problems, and less applicable to revolutionary design [101].








On the other hand, UTE provides a good framework to map the requirements with the design and technology variables. This mapping can be visualized using a parametric model indicating the variation of the responses as a function of the input variable settings. The environment allows the decision makers to play “*what if*” games by dynamically changing the input variables. Also, having a mathematical mapping makes it easier to propagate the uncertainty or error through the model [120].






The Unified tradeoff environment provides a good foundation for a quantitative requirements modeling process. A summary of the UTE properties are listed in Table 3.10.

Table 3.10: Summary of Unified Tradeoff Environment Properties

Advantages of UTE	UTE Limitations
<ul style="list-style-type: none"> - Assess the impact of requirements on concepts and technologies - Visualization the interactions - Provide the capability to the decision maker to play “<i>what if</i>” games - Allow the propagation of uncertainty through the environment 	<ul style="list-style-type: none"> - No traceability with the requirements definition process - Assume a fixed set of requirements (lack of flexibility) - Cannot be used with qualitative information - Cannot model the dynamic behavior of the customers[101] - The importance of a requirement can only be assessed if a mathematical model exist

The advantages and limitations of UTE are compared with respect to the proposed methodology criteria in Figure 3.24. Since the proposed methodology is focusing on the initial mapping of the requirements whereas UTE focuses on the final mapping with the systems alternatives, it is expected to obtain poor comparisons with the criteria defined in section 3.3. This method has been reviewed to obtain a full spectrum of approaches from purely qualitative to purely quantitative and learn from their respective advantages and disadvantages.

	UTE
(1) Structured systems decomposition	
(2) Common framework	
(3) Assure traceability	
(4) Use both qualitative/quantitative data	
(5) Assist the user to define importance	
(6) Allow uncertainty analysis	
(7) Manage information	

Excellent
Very Good
Good
Fair
Poor

Figure 3.24: UTE qualitative comparison with respect to mapping criteria.

3.4 Requirements Uncertainty Analysis

The objective of the requirements uncertainty analysis is to explore how uncertainty in the requirements affects the ranking and down-selection of requirements. This section on requirements uncertainty is intended to explore the literature regarding the third and fourth research questions:

RQ3: How to model subjective requirements?

RQ4: How to assess the uncertainty in the requirements mapping?

The goal of this section is to explore the inherent uncertainty present in conceptual design. According to DeLaurentis et al. (2000), uncertainty in the context of multidisciplinary

analysis can be defined as follows[40]:

“Uncertainty is the incompleteness in knowledge (either in information or context), that causes model-based predictions to differ from reality in a manner described by some distribution function.”

In general, uncertainty can be viewed as a state of knowledge, and the level of uncertainty varies as a function of what is known versus unknown with respect to a given set of assumptions. Uncertainty analysis has been extensively studied in the field of nuclear engineering, and systems safety & reliability [71, 69, 70, 138]. In the literature two major types of uncertainty are studied, aleatory (stochastic) and epistemic (subjective) [71, 84].

Aleatory uncertainty refers to the variability in a physical system’s characteristics and behaviors. For example, tolerances associated with the physical dimensions of a system represent aleatory uncertainty. This type of uncertainty is said irreducible, meaning that more information or new knowledge is not decreasing the level of uncertainty.

On the other hand, epistemic or subjective uncertainty corresponds to the lack of information and/or knowledge about a physical system’s characteristics and behaviors. For instance, the definition of the relationships in the QFD process represents a subjective uncertainty. This type of uncertainty is reducible, because more information or new knowledge can be used to reduce the level of uncertainty.

According to Helton (1993) “... *stochastic uncertainty is a property of the system under study, while subjective uncertainty is a property of the analysts performing the study*” [71]. Since this research is focusing on the mapping defined by the analysts, there will be more emphasis put on the epistemic uncertainty.

Knowing the different types of uncertainty is helpful to understand the uncertainty analysis process. According to Green et al. (2006) in a publication on the “*Decision Support Methods and Tools*” used at NASA Langley Research Center (LaRC), the uncertainty analysis is divided into three phases: quantification, propagation and decomposition [61]. During the quantification phase, the design team assesses the uncertainty surrounding the qualitative and quantitative information. This task can be achieved by assuming distribution and

range (min-max) on qualitative or quantitative input variables. In the propagation phase, the distributions are applied to the respective qualitative or quantitative model. At the decomposition phase, the results of the propagation are analyzed to evaluate the variability of the outputs with respect to the assumed uncertainty inputs.

In this section of the literature review, two uncertainty analysis approaches are discussed: sensitivity analysis and Monte-Carlo methods. The criteria for the comparison of the uncertainty techniques are described as follows:

- I. Handle large uncertainty: can be used with both linear and non-linear models;
- II. Flexible to integrate to the requirements mapping and down-selection approaches;
- III. Simple to use: making the analysis accessible to a majority of users;
- IV. Explore the uncertainty space: efficiently capture and visualize the model uncertainty.

Simplicity is required to facilitate the application of the methodology, and flexibility is required for its integration with the requirements mapping and down-selection approaches. Other techniques like Fuzzy set theory were also considered [203, 204] (Appendix B), however this approach requires the creation of fuzzy rules in addition to the selection of membership functions; consequently reducing the simplicity of the proposed methodology.

3.4.1 Sensitivity Analysis

Sensitivity Analysis (SA) consists of perturbing input variables and looking at the impact of the changes on the variability of the responses. As emphasized by Alexander (1994), the results of a sensitivity analysis may influence or alter the decisions of the users [6]. If it does then the problem or system is said “*sensitive*” to the variability of the variable.

This section is divided in three parts; it starts with an enumeration of the SA objectives, followed by a description of the theory used in SA technique, and it ends with a literature survey divided in three areas: theory, uncertainty application, and SA process combined with hierarchical model.

Sensitivity analysis can be used for multiple purposes [28]: “(i) *help visualize the impact of changes at the policy and strategy levels on decision at the operational level*; (ii) *test the robustness of a decision* [74]; (iii) *identify the critical elements of the decision* [8, 175]; (iv)

generate scenarios of possible rankings of decision alternatives under different conditions [194]; (v) *help judgment providers (the experts) reach consensus* [198]; and (vi) *offer answer to “what if” questions.*”

There are many sensitivity analysis alternatives including differential analysis [71], variance based methods [71], probabilistic methods [62] and entropy based methods [105, 103]. Most of these methods are based or derived from differential analysis principles, therefore this section will be focusing on the differential analysis approach.

The differential form of a linear system sensitivity analysis is depicted in Eq. 3.6:

$$\begin{aligned} y &= ax + b \\ y + \Delta y &= a(x + \Delta x) + b \end{aligned} \tag{3.6}$$

Where x represents the design variables, y the response, a and b the linear systems coefficients. In Eq. 3.6 the linear system is perturbed by Δx and it is desired to assess the response variability Δy . A more general differential form can be obtained using Taylor series expansion on y as depicted in Eq. 3.7 (problem setup), Eq. 3.8 (first-order derivation) and Eq. 3.9 (second-order derivation) [71].

$$\begin{aligned} y &= f(x_1, x_2, \dots, x_n) = f(\mathbf{x}) \\ \mathbf{x}_0 &= [x_{10}, x_{20}, \dots, x_{n0}] \end{aligned} \tag{3.7}$$

Where y represents the function of interest and \mathbf{x}_0 represents the vector including the n base values of the input variables.

$$y(\mathbf{x}) \simeq y(\mathbf{x}_0) + \sum_{j=1}^n \left[\frac{\partial f(\mathbf{x}_0)}{\partial x_j} \right] (x_j - x_{j0}) \tag{3.8}$$

$$\begin{aligned} y(\mathbf{x}) &\simeq y(\mathbf{x}_0) + \sum_{j=1}^n \left[\frac{\partial f(\mathbf{x}_0)}{\partial x_j} \right] (x_j - x_{j0}) \\ &+ \frac{1}{2} \sum_{j=1}^n \sum_{k=1}^n \left[\frac{\partial^2 f(\mathbf{x}_0)}{\partial x_j \partial x_k} \right] (x_j - x_{j0})(x_k - x_{k0}) \end{aligned} \tag{3.9}$$

As it can be seen from the previous equations, differential SA techniques require the evaluation of partial derivatives to evaluate the influence of the input on the output variables.

The propagation of the uncertainty in the model can be done by calculating the expected value and variance of equations 3.8 & 3.9 over a range of input values (i.e., $[x_{j0}$ to $x_j]$). The entire process is described in Reference [71]. The decomposition process is often visualized with graphics, as shown in Figure 3.25.

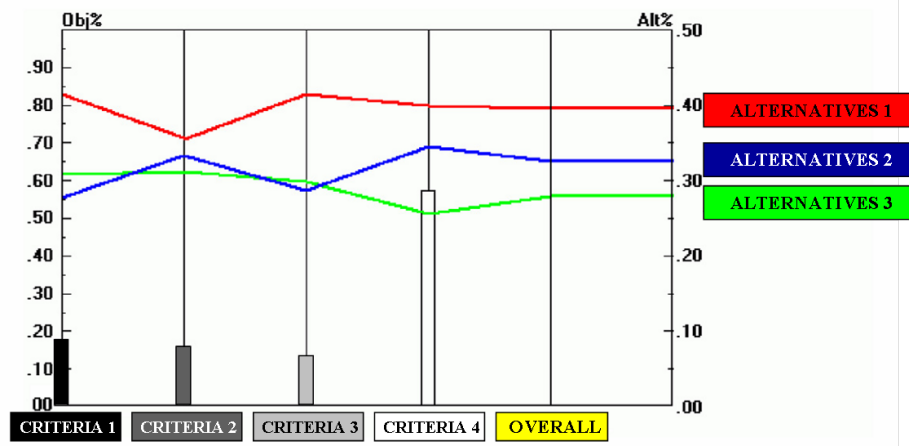


Figure 3.25: SA decomposition example (modified from [27]).

Figure 3.25 shows the priority of three alternatives as a function of four decision making criteria. The y -axis on the left side represents how the alternatives meet the objective function, whereas the y -axis on the right side represents the magnitude of the decision criteria. Consequently, an approach frequently used to perform SA consists of changing the magnitude of the criteria through scenarios and compare the resulting graphics to evaluate the changes in the alternative ranking.

The remainder of this section presents the SA literature survey conducted in this research. It is divided in three categories: SA theory, SA uncertainty applications, and SA combined with hierarchical model. A summary of the SA literature survey is presented in Table 3.11.

There are some recurrent themes in the SA publications. Most of the sensitivity analysis techniques require the evaluation of partial derivatives to propagate the uncertainty in the model. Partial derivatives imply a more local exploration of the uncertainty space, this is particularly true for non-linear models. For linear models SA is rapid and flexible, however as the non-linearity of the model increases the higher-order effects become more tedious to capture analytically, as depicted in Eq. 3.9. This drawback reduces the simplicity of the SA

Table 3.11: Summary of SA literature review.

Research Area	Ref.	Year	Authors	Objective
SA Theory	[6]	1989	Alexander	Develop several sensitivity indicators to answer the question “ <i>how sensitive is sensitive?</i> ”
SA Uncertainty	[71]	1993	Helton	Compare uncertainty and SA techniques applied to radioactive waste disposal assessment
	[62]	2004	Liu et al.	Compare four Probabilistic SA techniques to determine the sensitivity coefficients
	[103]	2006	Liu et al.	Apply entropy based Probabilistic SA to robust and reliability based designs
	[84]	2007	Guo et al.	Apply SA with mixed epistemic and aleatory uncertainties to evaluate plausibility and belief measures.
SA & Hierarchy	[116]	1990	Masuda	Describe theorems for hierarchical SA applied to AHP priority values
	[175]	1997	Triantaphyllou et al.	Compare integrated SA with AHP, weighted sum and weighted product models
	[27]	2007	Chang et al.	Apply AHP & sensitivity analysis to select the best alternative
	[28]	2008	Chen et al.	Develop a sensitivity analysis algorithm for additive aggregation technique

process. A qualitative comparison of the SA process with respect to the uncertainty analysis criteria is shown in Figure 3.26.

3.4.2 Monte-Carlo Methods

Monte-Carlo (MC) methods have been used extensively for problems considered too difficult to solve analytically. One of the early use of Monte-Carlo simulations was in 1930’s when Fermi used the technique to calculate the properties of a newly discovered neutron [32]. The formal Monte-Carlo methods with the foundation of the Probability Density Functions (PDF) and Cumulative Distribution Functions (CDF) was developed by von Neumann in the 1940’s [32]. This section describes the Monte-Carlo methods theory and includes a literature survey of publications using MC methods in uncertainty analysis.

The Monte-Carlo simulation process is illustrated in Figure 3.27. The process starts by selecting distributions for the desired inputs (x_i) of the model (1). Based on these

	SA
(1) Handle large uncertainty	○
(2) Flexible integration	◐
(3) Simple to use	◑
(4) Explore the uncertainty space	○






 Excellent	 Very Good	 Good	 Fair	 Poor
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Figure 3.26: SA qualitative comparison with respect to uncertainty criteria.

distributions, a random sample (\mathbf{x}_i) of the variables is created to perform m simulations (2). The next step (3) consists of running the model, m times, to calculate the desired responses (y_i) for each case of the random sample. The results are then collected and synthesized in the form of PDF and CDF (4).

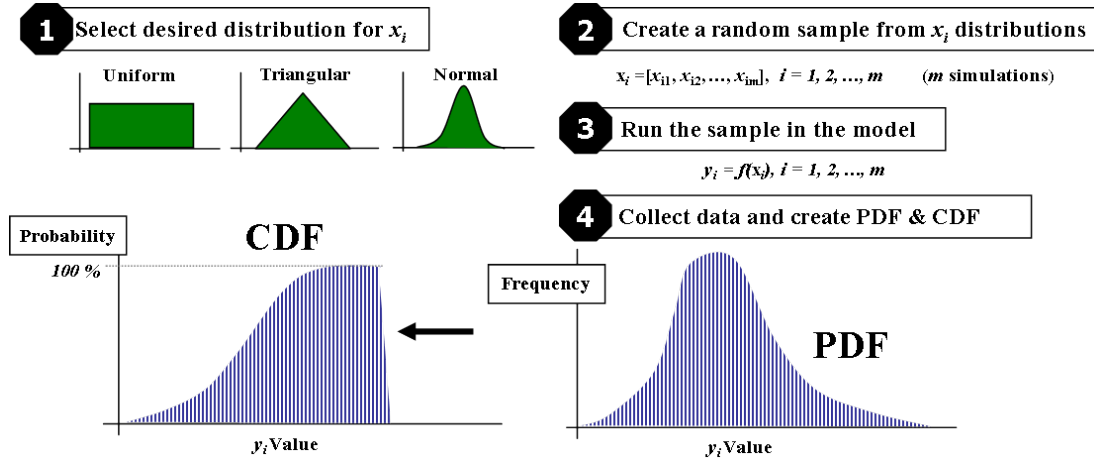


Figure 3.27: Monte-Carlo simulations process.

The PDF illustrates the frequency of the response as a function of the response values. The PDF curve is used to calculate the probability of obtaining a value Y given a specific range $[a, b]$, as formulated in Eq. 3.10:

$$P(a \leq Y \leq b) = \int_a^b f(y) dy \quad (3.10)$$

where $f(y)$ represents the PDF function. The CDF corresponds to the integral of the PDF function, consequently it represents the probability that a response value Y is less than a given threshold Z , as formulated in Eq. 3.11:

$$F(Z) = P(Y \leq Z) = \int_{-\infty}^Z f(u) du \quad (3.11)$$

where $f(u)$ represents the CDF function. Consequently, by assessing the uncertainty on the input variables, and propagating the uncertainty in the model, the responses become probabilistic. For more than one dimension, the joint probability approach can be used to compare the correlation between the responses [13], as illustrated in Figure 3.28.

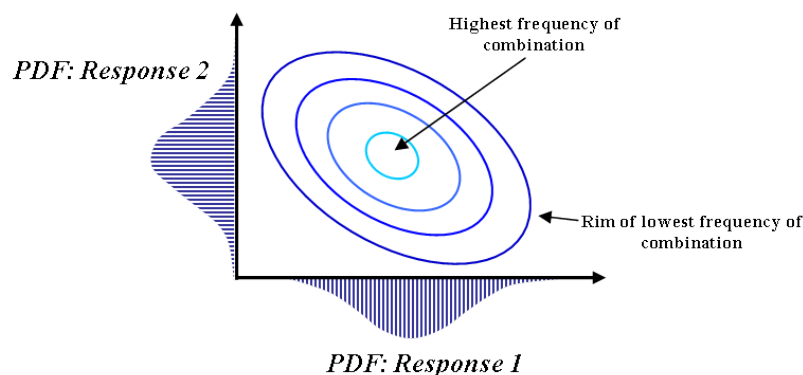


Figure 3.28: Example of joint probability distributions.





The uncertainty analysis with Monte-Carlo methods is simple and provides great flexibility to integrate the uncertainty propagation to practically any numerical model. Consequently the MC methods literature is quite extensive. For the current research, an effort was made to concentrate the search for publications specifically related to uncertainty analysis. Also other publications were included in the literature search to provide examples of application; for instance the Monte-Carlo methods applied to technology forecasting and reliability theory. A summary of the MC methods literature survey is depicted in Table 3.12.

From the information gathered in this literature survey, it is possible to generalize that

Table 3.12: Summary of Monte-Carlo methods literature review.

Research Area	Ref.	Year	Authors	Objective
MC Uncertainty	[71]	1993	Helton	Implement MC methods to assess the performance of radioactive waste disposal
	[40]	2000	DeLaurentis et al.	Apply MC methods in uncertainty model in the context of multi-disciplinary analysis
	[12]	2001	Baker et al.	Apply MC methods with UTE to bound the requirements space
	[23]	2001	Cagno et al.	Combine MC methods and AHP to assess the probability of winning a competitive bidding process
	[69]	2004	Helton et al.	Explore uncertainty models prediction: probability theory (MC), evidence theory, possibility theory, and interval analysis
	[61]	2006	Green et al.	Discuss how NASA LaRC use MC methods to propagate uncertainty in aerospace design
MC Technology	[118]	1998	Mavris et al.	Use MC methods to forecast the impact of new technologies in aerospace systems design
	[92]	2001	Kirby	Integrated MC methods in technology identification, evaluation and selection methodology
MC Reliability	[24]	2008	Cardoso et al.	Determine probability of structural failure by combining MC methods and neural networks models

[71]: (1) MC methods can assess uncertainty for both linear and non-linear models, consequently they can handle large uncertainty; (2) MC methods are highly flexible and can be integrated in most processes; (3) the technique is simple to use and a novice user can learn it relatively rapidly; (4) MC methods explore the design space randomly, therefore with a large number of simulations it is possible to capture most of the uncertainty space. The major drawback of Monte-Carlo methods is the computational cost, especially if the numerical model takes a long time to run. It is for this reason that surrogate modeling techniques, like response surface methods and neural-networks, are often combined with the MC methods in order to reduce the computational time. A qualitative comparison of the MC methods with respect to the uncertainty analysis criteria is shown in Figure 3.29.

	MC
(1) Handle large uncertainty	
(2) Flexible integration	
(3) Simple to use	
(4) Explore the uncertainty space	






				
Excellent	Very Good	Good	Fair	Poor

Figure 3.29: Monte-Carlo qualitative comparison with respect to uncertainty criteria.

3.5 Requirements Down-Selection & Resource Allocation

The requirements down-selection and resource allocation are closely related research areas, as emphasized in the following quotes from a General Accounting Office report [180]:

“...when requirements and resources were matched before product development was started, the more likely the development was able to meet performance, cost, and schedule objectives.”

Also the same report states that the “*key to the successful cases (projects) was the ability to make early trade-offs either in the design of the product or in the customer’s expectations to avoid outstripping the resources available for product development.*” The objective of down-selection and resource allocation in this research is to use the available information from the requirements mapping and uncertainty analysis to make early trade-offs between stakeholder expectations and systems alternatives, and ultimately have an estimation of the required resources.

This section is intended to explore the literature regarding the last two research questions:

RQ5: What are the down-selection criteria that can be used with the hierarchical model?

RQ6: How to allocate resources to requirements in conceptual design?

The first part of the section includes a discussion on the criteria desired to perform the down-selection and resource allocation in the context of this work; while the second part includes the literature surveys of two approaches considered for the proposed methodology.

The down-selection of requirements in conceptual design constitutes a critical decision making problem. Many techniques can be used to perform this task, however depending on the application some techniques are better than others, as highlighted by Li (2007) in his work on Multi-Criteria Decision Making [102]. In the scope of this research, it is desired to understand how the requirements mapping and subjective uncertainty influence the relative importance of requirements. The desired criteria for the requirements down-selection and resource allocation are the following:

- I. Common Framework: with requirements mapping and uncertainty analysis;
- II. Provide concise criteria for down-selection;
- III. Use both qualitative/quantitative information;
- IV. Traceability: with the initial requirements mapping;
- V. Flexibility: take into account the uncertainty analysis;
- VI. Simplicity: to understand and use the approach for a new user.

These criteria are consistent with the requirements mapping and uncertainty analysis section. Since the knowledge acquired in these areas is used to down-select the requirements, these criteria were selected to facilitate the transition between the different steps of the proposed methodology. The two approaches considered are the (1) AHP/ANP and (2) Benefits-Costs analysis.

3.5.1 AHP/ANP Down-Selection and Resources allocation

The general theory and applications of the AHP/ANP techniques were discussed in sections 3.3.3 and 3.3.4 respectively. This section focuses on how these approaches can be applied to down-select alternatives and allocate resources. This section discusses the desirability index for the down-selection and the relative linear programming for the resource allocation.

The desirability index aggregates the results from the AHP pairwise comparisons model, to determine the preference of the alternatives. Figure 3.30 shows a hierarchical model

including a goal, criteria, metrics, and alternatives that will be used as notional example in this section.

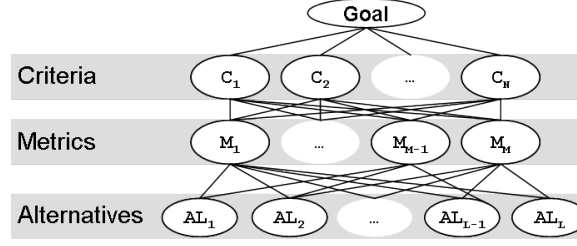


Figure 3.30: Notional hierarchical structure.

This desirability index of an alternative is calculated in a two steps process as depicted in Eq. 3.12 [121].

$$D_{ijk} = \sum_{i=1}^L \sum_{j=1}^N \sum_{k=1}^M C_j M_k A_i$$

$$\tilde{D}_i = \sum_{j=1}^N \sum_{k=1}^M D_{ijk}$$
(3.12)

Where C_j , M_k and A_i represent the relative importance resulting from the pairwise comparisons for the criteria, metrics and alternatives respectively. The first step is to multiply the relative importance for all the branches of the hierarchy to obtain D_{ijk} . The next step is to aggregate these results for each alternative, where the greatest value of \tilde{D}_i indicates the “best” alternative based on the comparisons input to the model. It should be noted, that this technique requires all the alternatives to be mapped to at least one element per level of the hierarchy (metrics and criteria). Also, the number of summations in Eq. 3.12 depends on the number of levels of the hierarchy.

Based on the results of the desirability, one can rank the alternatives in terms of preferences and identify the resources required to design the alternatives. To allocate the resources, Saaty et al. (2003) developed a technique allowing the allocation of both tangible (i.e., money, man hour, weight, etc.) and intangible (i.e., product quality, brand image, safety, etc.) resources [159]. This technique is based on a relative linear programming algorithm as formulated in Eq. 3.13.

$$\begin{aligned}
\text{Decision variables: } & \vec{w} = (w_1, \dots, w_n)^T \\
\text{Objective function: } & \text{Maximize } \rightarrow Z = \sum_{j=1}^n c_j w_j \\
\text{Constraints: } & \text{Subject to } \rightarrow \sum_{j=1}^n a_{ij} w_j \leq b_i
\end{aligned} \tag{3.13}$$

w_j represents the resource to allocate, c_j the relative weight of the criteria with respect to the allocation goal, a_{ij} the resource weight with respect to the criteria and b_i the amount of resources. If the resources are tangible, then b_i has the same unit as the resources; if they are intangible, then b_i is non-dimensional and its value represents the relative importance of the resource.

For example, Saaty et al. (2003) compared two firms (alternatives) as a function of three areas; the Markets (MKTS), Innovation (I) and Cost reduction (C). He includes two tangible resources, Technical Human Resources (THR) and Managerial Human Resources (MHR) in dollars. The first step is to assess the use of the current resources with respect to the markets, innovation and cost reduction effort. For instance, it is known that firm A allocates 10%, 70% and 20% of THR to the markets, innovation and cost reduction effort, respectively. The second step is to evaluate how the respective areas contribute to the total worth of the company. Table 3.13 lists the relative contribution of the resources and company worth with respect to the markets, innovation and cost reduction effort of Firm A.

Table 3.13: Resource allocation example [159].

Firm A	%THR (a_{1j})	%MHR (a_{2j})	Areas vs. company worth (c_j)
Markets	0.1	0.3	0.49
Innovation	0.7	0.1	0.20
Cost Reduction	0.2	0.6	0.31

$$b_1 = \text{THR} = 182 \text{ \$M}$$

$$b_2 = \text{MHR} = 435 \text{ \$M}$$

The objective function in this example corresponds to the total worth of the company, and consequently the relative linear algorithm of Eq. 3.13 becomes:

Firm A

$$Max Z_A = 0.49w_{11} + 0.20w_{12} + 0.31w_{13}$$

subject to

$$0.10w_{11} + 0.70w_{12} + 0.20w_{13} \leq 182$$

$$0.30w_{11} + 0.10w_{12} + 0.60w_{13} \leq 435$$

$$w_{ij} \geq 0$$

By solving this model it can be found that the total worth of Firm A is maximized by allocating its resources in the markets ($w_{11}= 1431.5$) and innovation ($w_{12}=55.5$) and none to the cost reduction ($w_{13}=0$).

A summary of the publications discussing the use of AHP/ANP for down-selection and resource allocation are listed in Table 3.14.







Table 3.14: AHP/ANP down-selection and resource allocation literature review.






Research Area	Ref.	Year	Authors	Objective
Down-Selection	[111]	1998	Maiden et al.	Discuss how AHP can be used to acquire Commercial off-the-shelf software
	[59]	1998	Ghodsypour et al.	Use AHP and Linear Programing (LP) to select the best suppliers and how much to purchase from them
	[170]	2001	Tam et al.	Apply AHP to select a telecommunication system vendor based on 33 factors organized in 4 hierarchical levels
	[27]	2007	Chang et al.	Application of AHP to select the best alternative with 2 levels of criteria
Resource Allocation	[121]	2002	Meade et al.	Use ANP to select R&D project based on a hierarchy of criteria
	[159]	2003	Saaty et al.	AHP resource allocation of tangible and intangible resources using relative LP
	[158]	2007	Saaty et al.	Apply AHP and LP to optimize human resources allocation
	[78]	2008	Hsu et al.	Allocate resource based on the priority values: applied to competitive advantage model

This survey of the literature shows that ANP/AHP can be used for both down-selection and resource allocation. Consequently, it can be easily integrated to the hierarchical decomposition of the systems, and at the same time provide continuity in the traceability of the information. Furthermore, as demonstrated in Reference [159], AHP can be used to

allocate both tangible and intangible resources. In terms of simplicity, the down-selection and resource allocation may require some additional pairwise comparisons, and the relative linear programming algorithm is the only new theory added to the AHP/ANP methods.

In summary, this approach is mapped to the desired criteria of the requirements down-selection and resource allocation in Figure 3.31.

	AHP/ANP
(1) Common framework	
(2) Provide concise criteria	
(3) Use both qualitative/quantitative data	
(4) Assure traceability	
(5) Flexibility	
(6) Simplicity	

Excellent
Very Good
Good
Fair
Poor

Figure 3.31: Qualitative comparison for AHP/ANP down-selection and resource allocation.

3.5.2 Benefits-Opportunities-Costs-Risks Analysis

This section is meant to address the fifth research question regarding the down-selection criteria. While designing complex systems, there are a large number of potential down-selection criteria. These criteria will differ depending on the stakeholders and the systems considered. The hierarchical model can thus include different criteria at different levels of the hierarchy. However the final selection of requirements correspond to a top-level goal that impacts all the objectives, metrics and alternatives below. Consequently, there needs to be some top-level criteria that synthesize all the lower level criteria. This section will discuss such top-level criteria, and how they can be integrated with the requirements mapping and uncertainty analysis.

Any design problem involves decisions that are favorable or unfavorable to the success of the project. Favorable decisions can be categorized as benefits or opportunities, while

unfavorable decisions can be classified as costs or risks. Such criteria can be integrated a hierarchical model as top-level criteria, Figure 3.32.

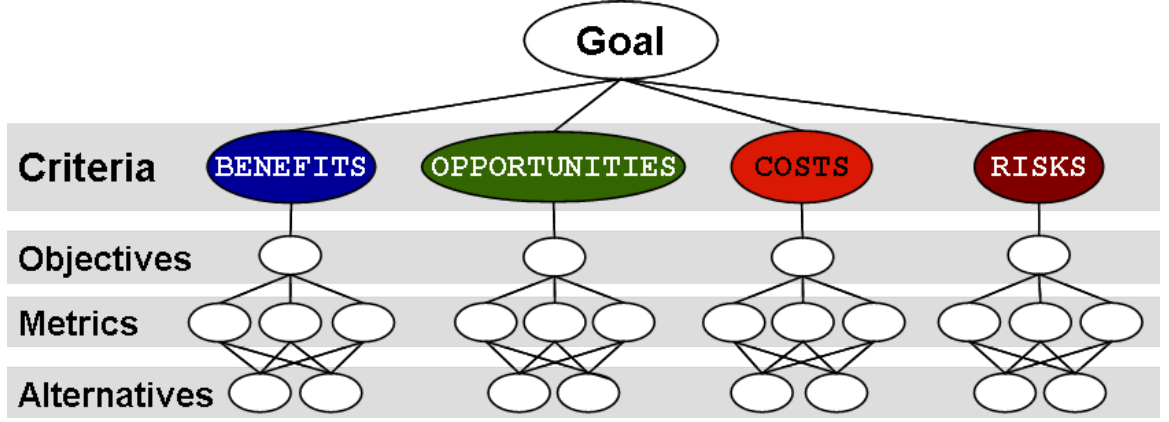


Figure 3.32: BOCR hierarchical model.

The model shown in Figure 3.32 is often referred to as Benefits, Opportunities, Costs and Risks (BOCR) [157, 155]. The BOCR criteria are then expanded into their respective hierarchical models, since one needs to assess the relative importance of the objectives, metrics and alternatives as a function of each criterion. In the AHP/ANP literature, three approaches are discussed to synthesize the BOCR [157, 193], these aggregation techniques are formulated in equations 3.14, 3.15, and 3.16.

$$\text{Multiplicative} : \frac{B_p^{w_b} \times O_p^{w_o}}{C_p^{w_c} \times R_p^{w_r}} \quad (3.14)$$

$$\text{Additive (reciprocal)} : w_b \times B_p + w_o \times O_p + w_c \times (1/C_p^*) + w_r \times (1/R_p^*) \quad (3.15)$$

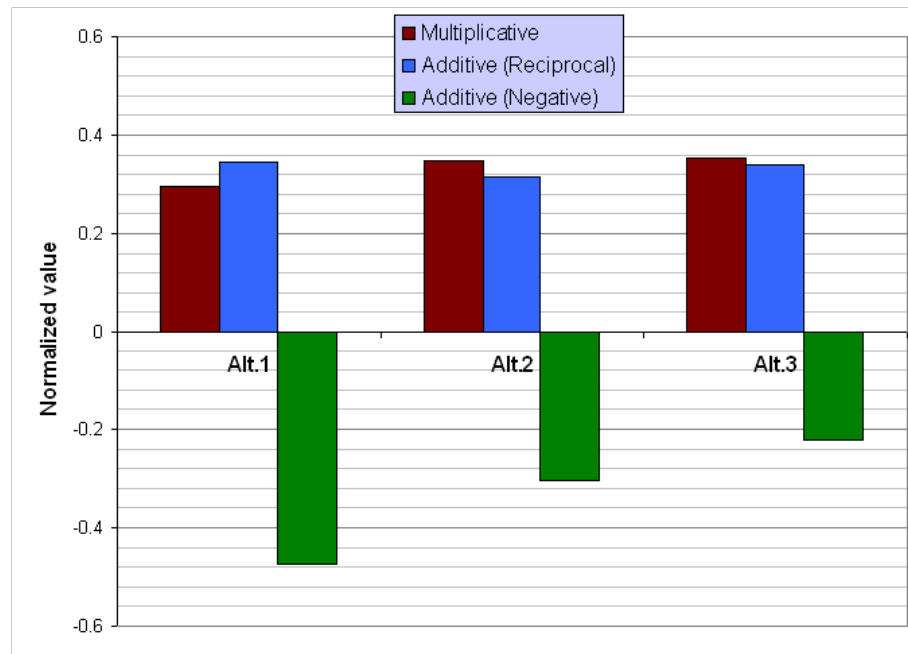
$$\text{Additive (negative)} : w_b \times B_p + w_o \times O_p - w_c \times C_p - w_r \times R_p \quad (3.16)$$

The stars in the Eq. 3.15 imply that the reciprocal values are normalized so that the sum of the reciprocal (e.g., $\sum 1/C_p^*$) is equal to 1. It is important to note that when the hierarchical models are created in terms of cost and risk, the metrics or alternatives are compared in terms of the *highest* costs or risk. Implying that the riskier alternative is the one with the highest numerical value. Table 3.15 presents an example of a BOCR using the three different synthesis approaches for three alternatives.

Table 3.15: BOCR synthesis approaches [157, 193].

	Benefits (0.184) B_p	Opportunities (0.263) O_p	Costs (0.228) C_p	Risks (0.326) R_p	1/Costs (0.228) $1/C_p^*$	1/Risks (0.326) $1/R_p^*$
Alt.1	0.097	0.112	0.191	0.167	0.514	0.552
Alt.2	0.461	0.356	0.391	0.374	0.251	0.247
Alt.3	0.442	0.532	0.418	0.459	0.235	0.201
Sum	1.000	1.000	1.000	1.000	1.000	1.000

The values between parentheses represent the weighting of the criteria (w 's). The different synthesis techniques are illustrated in Figure 3.33 to visually differentiate the approaches.

**Figure 3.33:** Example of BOCR synthesis.

It can be noticed that in Figure 3.33 the different approaches result in a different ranking of the alternatives. The multiplicative technique gives $Alt1 > Alt3 > Alt2$, while both additive techniques result in $Alt3 > Alt2 > Alt1$. In the literature, the additive (negative) approach is generally preferred over the other approaches [188, 157, 123, 193]. This preference is validated with examples demonstrating that the additive (negative) technique provides more intuitive results while preserving the unit of the criteria. For example, if the results are expressed in monetary values, this technique allows the evaluation of the “net” benefits of the decision. Therefore, a synthesized result greater than zero indicates that the alternative

provides more benefits and opportunities than costs and risks. It can thus be considered “*profitable*” to select this alternative.

The literature review on the BOCR analysis has been divided in two categories, (1) theory and (2) application. A summary of the literature survey is listed in Table 3.16.

Table 3.16: Summary of BOCR analysis literature review.







Research Area	Ref.	Year	Authors	Objective
Theory	[188]	1997	Vargas	Emphasize the axioms behind the AHP synthesis process
	[157]	2001	Saaty	Discuss the foundation and theory behind the use of BOCR analysis integrated with ANP
	[123]	2005	Millet et al.	Justify the importance of the additive synthesis with negative preferences
	[193]	2007	Wijnmalen	Compare the different synthesis approaches for BOCR
Application	[160]	1990	Saaty	Early applications of benefits-Costs analyses performed with AHP
	[177]	1997	Tummala et al.	Assess the benefits and costs to implement concurrent engineering in the Hong Kong electronics industry
	[124]	2002	Millet et al.	Apply benefits-risks analysis to model risk and uncertainty with AHP
	[155]	2006	Saaty et al.	Describe nine case studies on the application of ANP with BOCR






From the literature survey, it has been observed that the BOCR analysis is utilized when dealing with complex problems involving a large number of criteria being categorized under benefits, opportunities, costs and risks. On the one hand, the AHP down-selection process evaluates the desirability of alternatives based on the synthesis of relative importance. The criteria often implies some type of benefits, opportunities, costs and risks without being explicitly stated, and the comparison are only based on the notion of relative importance.

On the other hand, the BOCR analysis allows the evaluation of the relative importance explicitly in terms of benefits, opportunities, costs or risks. The synthesis of the results is not in terms of desirability, but provide a multi-dimensional perspective for the decision making process. Consequently, the experts have the additional freedom to indicate their preferences in terms of benefits, opportunities, costs and risks. For instance, if the monetary resources for the project are very limited, more emphasis can be put on the costs and risks then on

the benefits and opportunities.

When compared to the requirements down-selection criteria, the BOCR analysis is deemed to provide more concise criteria than the conventional AHP/ANP down-selection approach. However, additional hierarchies require performing more pairwise comparisons which tends to reduce the simplicity of the approach. The complete qualitative comparison of the BOCR approach with respect to the methodology down-selection process is illustrated in Figure 3.34.

	BOCR
(1) Common framework	
(2) Provide concise criteria	
(3) Use both qualitative /quantitative data	
(4) Assure traceability	
(5) Flexibility	
(6) Simplicity	

Excellent
Very Good
Good
Fair
Poor

Figure 3.34: Qualitative comparison for BOCR analysis with respect to the methodology criteria.

3.6 Summary of the Literature Review

To summarize this chapter, this section combines the qualitative comparison of the proposed methodology criteria and approaches discussed in the literature survey. For each of the criteria, the “*best*” approach is highlighted in order to create a contrast with the other tools.

The requirements mapping represent the core of the proposed methodology, in section 3.3 five approaches were considered from fully qualitative mapping (GOTChA) to fully quantitative mapping (UTE), as illustrated in Figure 3.35.

The QFD process can be considered as the current baseline approach, since it has been extensively studied in the academia and applied in the industry. With respect to these criteria, AHP/ANP is considered better because of its structure that resembles the structure

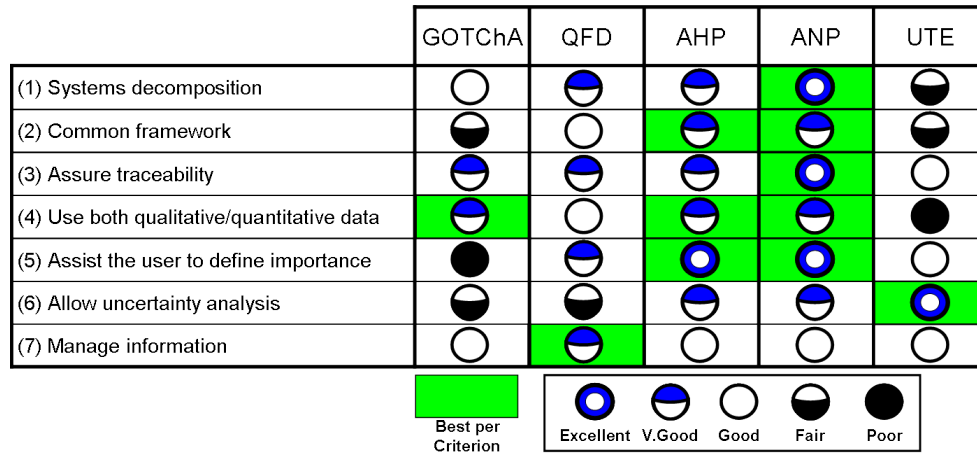


Figure 3.35: Requirements mapping qualitative comparison summary.

of the complex systems that need to be analyzed. The ration scale basis of AHP/ANP allows the use of both qualitative and quantitative information. Also due to its flexibility, it is possible to assure the traceability of the information at different levels of the problem, even during the uncertainty analysis and requirements down-selection.

The requirements uncertainty analysis area was addressed in section 3.4. Due to the large uncertainty inherent to the requirements analysis phase, the desired approach should be able to handle large uncertainty and at the same time being able to explore most of the uncertainty space. Also the technique should be flexible to facilitate the integration with the requirements mapping and simple to use by the experts. Figure 3.36 shows the combined qualitative comparison of both approaches considered.

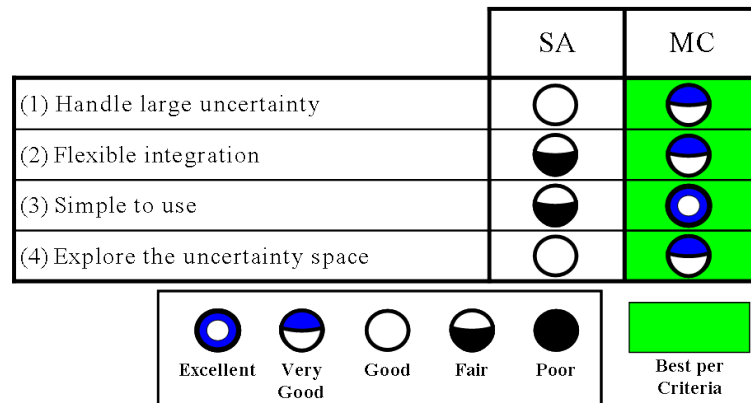















Figure 3.36: Requirements uncertainty analysis qualitative comparison summary.


Figure 3.36 indicates that the Monte-Carlo methods have a greater potential of handling


large uncertainty, being flexible and simple to use. However, one of the drawbacks of the Monte-Carlo methods is the computational time, consequently during the construction of the proposed methodology it will be analyzed if this drawback is acceptable or not in the context of requirements analysis.


The last research area of requirements down-selection and resource allocation was discussed in section 3.5. As for the uncertainty analysis, this process is meant to be integrated with the requirements mapping in order to assure the traceability of the information. For that reason the AHP/ANP was discussed specifically as regarding its down-selection and resource allocation dimensions.


	AHP/ANP	BOCR
(1) Common framework		
(2) Provide concise criteria		
(3) Use both qualitative /quantitative data		
(4) Assure traceability		
(5) Flexibility		
(6) Simplicity		


Excellent


Very Good


Good


Fair


Poor



Best per Criteria

Figure 3.37: Requirements down-selection and resource allocation summary.

The Benefits-Opportunities-Cost-Risks criteria are frequently combined with AHP & ANP to provide synthesized top-level criteria for the selection of alternatives. In reality there exist a great number of criteria that can be associated to specific systems, but when all the systems are integrated together it becomes difficult to capture their importance. Consequently, the BOCR criteria can be added to the decision model structure to provide top-level criteria during the synthesis of the lower level criteria.

Chapter IV

RESEARCH APPROACH AND METHODOLOGY

The exploration of the research scope in Chapter 2 resulted in the identification of a set of research questions regarding specific “*gaps*” in the field of definition, modeling and selection of requirements. These research questions were regrouped in three areas, (1) requirements mapping, (2) uncertainty analysis and (3) requirements down-selection & resource allocation. At the beginning of Chapter 3, more than forty tools were listed, representing more than one million combinations, to potentially answer the research questions. From a preliminary literature survey combined with a set of desired criteria for the proposed methodology, nine tools were discussed in detail in Chapter 3. Therefore the objective of this chapter is to formulate research hypotheses based on the approaches presented in Chapter 3, in order to answer the research questions defined in Chapter 2.

Figure 4.1 outlines the observations (Chapter 1), research questions and methodology steps presented at the end of Chapter 2.

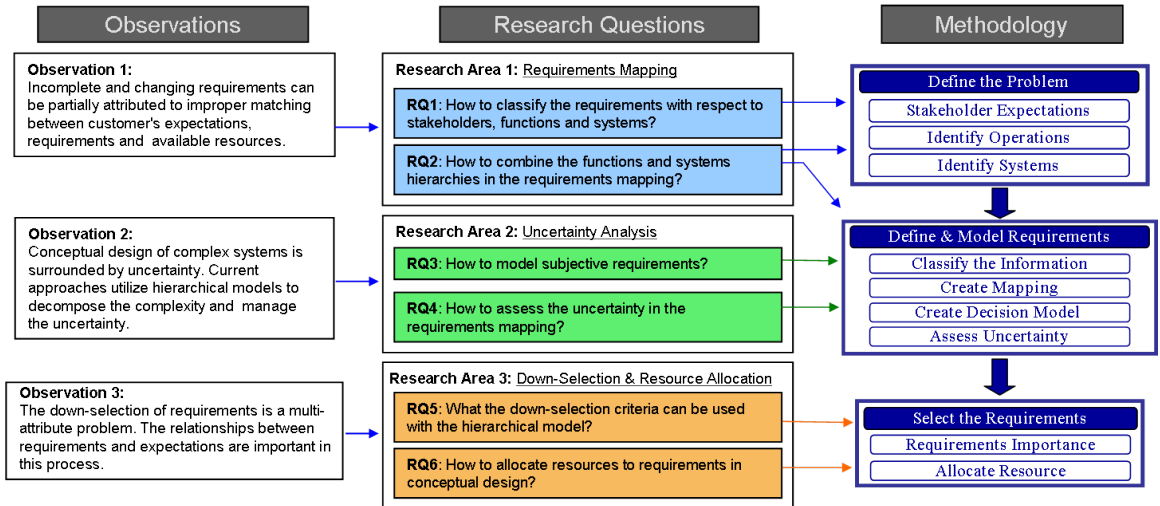


Figure 4.1: Recapitulation of observations, research questions and methodology.

4.1 Research Questions and Hypotheses

The research questions and hypotheses represent the foundation of this research. The research questions summarize the motivation and research scope by focusing on specific problems. In Section 1.2 one of the first challenges identified refers to the fact the incomplete and changing requirements are the main cause of project failures. In the same section, a report of the U.S. GAO on best practices describes that projects matching the stakeholder expectations, requirements and resources early in the design phase have a better chance of succeeding. That challenge led to the exploration of requirements decomposition and mapping, in Chapter 2, by looking at the current requirements analyses methodologies.

The requirements decomposition and mapping is the primary focus of this work, since the other two research areas are integrated to the logical decomposition of requirements. The requirements decomposition implies starting with the stakeholder expectations and identifying the functions, measures of effectiveness, systems and resources involved in the systems design. The requirements mapping consists of identifying the relationships between these various elements in order to assure the requirements traceability, verifiability and consistency (section 3.1.2).

The first step in order to assure the decomposition and mapping of requirements is to understand the different types of requirements and how they are related to the stakeholders, functions and systems. Formally, this leads to the first research questions defined as follows:

Research Question 1 (RQ1): How to classify the requirements with respect to stakeholders, functions and systems?

The types of requirements discussed in section 3.1 are taken from different fields of engineering, and one definition was selected for each type of requirement. The objective of Research Question 1 is to determine if there is a hierarchy between the different types of requirements and how this hierarchy can be used in order to manage the information while assuring the traceability, verifiability and consistency properties of the requirements. To provide a solution path to answer this research question, there needs to be some taxonomy that can be used as the basis of the classification and management framework. This is formally stated

as Hypothesis 1:

Hypothesis 1 (H1): The stakeholders, requirements and systems can be classified under a single taxonomy.

The taxonomy is intended to be used to help the design team understanding the origin of requirements, by creating relationships between stakeholders, functions and systems for each requirement. The management document associated with the taxonomy can then be used by the decision makers to track the requirements changes and at the same time knowing which other elements of the systems will be impacted by the changes.

In order to prove Hypothesis 1, first a requirements taxonomy needs to be created, and second it needs to be applied to a design problem to judge of its usefulness. The usefulness of the taxonomy can be measured by its simplicity (how easy it is to track a requirement) and its flexibility (is it general enough to be used to different applications).

The second research question specifically refers to the logical decomposition of requirements. During the identification and classification phase, functions and requirements are often regrouped in hierarchies. The hierarchical structure of information is a good way to represent how general concepts are divided into more specific components. The intent behind the second research question is to take advantages of the hierarchies created during the problem definition phase and combine them into the requirement analysis phase.

Research Question 2 (RQ2): How to combine the functions and systems hierarchies in the logical decomposition of the requirements?

The current approach of mapping the functions and systems to the requirements is performed by a sequence of tasks. The first task involves regrouping the functions and systems based on a set of criteria or common affinity. The affinity diagram is one of the tools that can be used for this task. Then the team selects a set of requirements that is considered important to the project (or provided by a RFP), and requirements are mapped with systems characteristics through the QFD process. The results of the first stage of the QFD, the house of quality, provide the design team with a qualitative assessment of the relationships

between requirements and systems characteristics. Based on a weighted sum calculation, the most important systems characteristics are identified, which helps the design team to identify potential systems alternatives that can satisfy the initial set of requirements.

This type of approach has been widely used since the first installment of the QFD process in the 1980s. After numerous applications by Japanese and American industries, the QFD process has been proven to reduce the uncertainty by increasing the efficiency in product design and improving the communication within the design team. On the other hand, relevant information is lost before and after the QFD, as the team transitions from the problem definition to the Analysis of Alternatives (AoA) .

In order to assure a better traceability in the flow of information, the requirements mapping needs to be related to the requirements taxonomy and to the AoA. From sections 3.7 and 3.9 of the literature review, it has been shown that the Analytic Hierarchy Process and its generalization, the Analytic Network Process, have the potential of improving the current requirements mapping processes. This assertion is formalized by the second hypothesis:

Hypothesis 2 (H2): The Analytic Network Process can be used as a common framework to map expectations, functions, systems and resources.

Based on the seven criteria established for the requirements mapping (section 3.3), ANP provides a common framework for the systems decomposition, while assuring the traceability between both qualitative and quantitative information. The AHP & ANP have been widely used for many different applications, but no reference was found in the literature that used ANP with a unified requirements analysis framework.

In order to prove Hypothesis 2, ANP needs to be applied to a design problem to demonstrate its traceability capability and how it handles both qualitative and quantitative information. As a common framework, ANP needs to be flexible enough to allow the integration of uncertainty and requirements down-selection techniques. This brings the third research question which is the requirements mapping and the uncertainty analysis research areas.

At the early stage of the conceptual design phase, the level of knowledge is relatively low whereas the level of uncertainty is relatively high. Therefore, when the stakeholders

express their expectations, there may exist a fair amount of subjectivity surrounding the requirements. This assertion is formalized by the third research question:

Research Question 3 (RQ3): How to model subjective requirements?

The modeling of subjective requirements involves the mapping and the understanding of epistemic uncertainty (section 3.4). This research question also relates to Hypothesis 2, since the logical decomposition of the systems has been shown to provide more information and knowledge about the system and thus reducing the uncertainty.

Providing a logical decomposition in a hierarchical or network framework allows the expert to focus on a reduced set of elements, which tends to improve the accuracy of the judgment (brain channel capacity section 1.2.3). Furthermore, ANP has the capability of reducing the subjective uncertainty by enabling the experts or design team to analyze the consistency of the pairwise comparisons with a consistency index (section 3.3.3). At this stage, even if the pairwise comparisons are not perfectly consistent, this feature can generate discussion within the team, which may eventually lead to the discovery of additional information to reduce the epistemic uncertainty.

Once the epistemic uncertainty is assessed, the next step is to propagate it through the requirements mapping to analyze how it may influence the down-selection of requirements. This activity refers to the fourth research question:

Research Question 4 (RQ4): How to assess and propagate the epistemic uncertainty in the requirements mapping?

While the second hypothesis is expected to reduce the uncertainty by improving the requirements mapping, there is a need to analyze how the variation in the decision model, represented by pairwise comparisons, impacts the relative importance of the functions, measures of effectiveness, and systems characteristics. Therefore, uncertainty analysis techniques, section 3.4, need to be integrated with the requirements mapping to achieve this purpose. Hypothesis 3 is formulated to provide a solution path for both RQ3 and RQ4:

Hypothesis 3 (H3): Uncertainty analysis techniques integrated with the requirements mapping, combining both qualitative and quantitative information can be used to reduce the epistemic uncertainty surrounding the requirements.

The combination of both qualitative and quantitative information is essential, since early in the design process it is easier for the stakeholders and designers to describe the systems in qualitative terms (e.g., long range). As the design progresses, more information becomes available and it becomes important to quantify the information in order to down-select the number of systems alternatives (e.g., range of 2000 nautical miles). The presence of quantitative information also helps the experts to revisit their decision model; for instance depending on the desired range the fuel and power capacity will more than likely change, which then generates some derived requirements.

With the definition of the requirements mapping and the analysis of the uncertainty, more requirements are likely to surface. One objective of the integrated framework is to assess the relative importance of the elements included in the decision model to reduce the set of requirements. Furthermore, any project is limited in term of resources (time, money, manpower, technology, etc.), consequently the down-selection of requirements and the allocation of resources are closely related activities. This research area refers to the last two research questions:

Research Question 5 (RQ5): What are the down-selection criteria that can be used with the hierarchical model?

Research Question 6 (RQ6): How to allocate resources to requirements in conceptual design?

Even though some specific criteria for the down-selection are established in the requirements mapping, as the synthesis of the systems is performed, there needs to be some top-level criteria evaluating the global impact of functions, systems MoEs and alternatives with respect to the project goals. Also, these criteria must reflect the types of resources available. At the same time, the down-selection process needs to be flexible to assure the traceability of the

information, and to allow the potential mapping of the resources with the respective systems characteristics. The down-selection and resource allocation techniques were discussed in section 3.5, which leads to the last hypothesis:

Hypothesis 4 (H4): A Benefits-Costs-Risks decision model can be combined with the requirements mapping and used for down-selection and resource allocation.

For this research, the Opportunity dimension in the BOCR analysis is left aside since in the literature most design problems only dealt with benefits (performance), costs and risks analyses. The opportunity dimension might have created some confusion, and thus reduce the usability of the proposed methodology. However, note that if this dimension is critical for the user, its integration only affects the synthesis of the relative importance (section 3.5.2) and can be easily incorporated to the decision model.

The flow of research questions and hypotheses is summarized in Figure 4.2.

4.2 Proposed Methodology

The steps of the proposed methodology are first defined after the review of the INCOSE, DoD and NASA requirements methodologies in Chapter 2. In Chapter 3, different approaches are described for each research area. These approaches represent the building blocks of this research, and the objective of this section is to formulate the proposed methodology by merging the requirements analysis steps with the reviewed approaches.

As mentioned in Chapter 2, this research focuses on the definition, modeling and selection of requirements. The definition phase involves market analysis, customer survey, focus group and the identification of the concept of operations (CONOPS). Even though some of these elements are used as inputs to the proposed methodology, this research does not provide new contributions in these fields, and consequently they are outside the scope of this research.

Figure 4.3 presents the steps of the proposed methodology, starting with the definition and modeling of requirements. Each of these steps are described in this section, however note that Step 2 (creation of the mapping) represents the core of the proposed methodology.

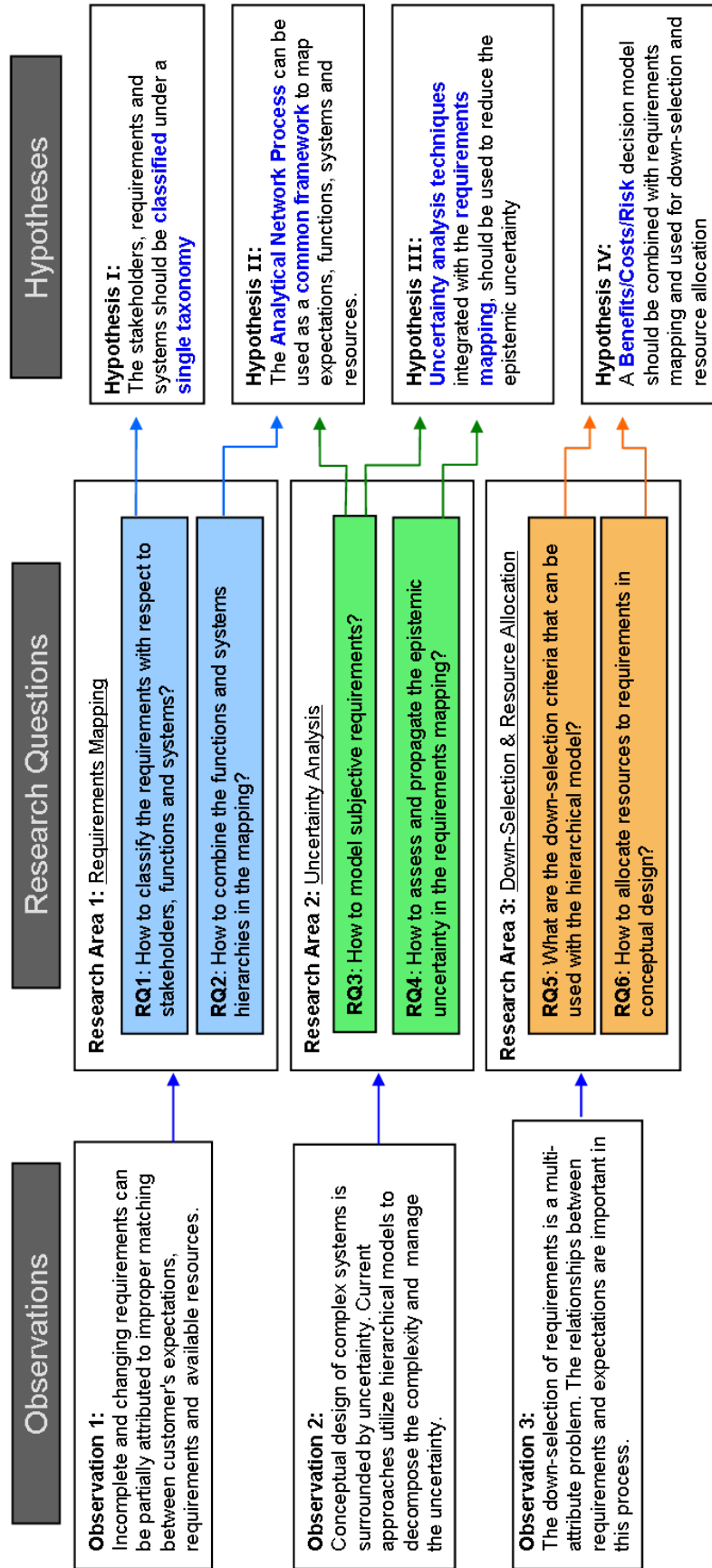


Figure 4.2: Summary of Research questions and hypotheses.

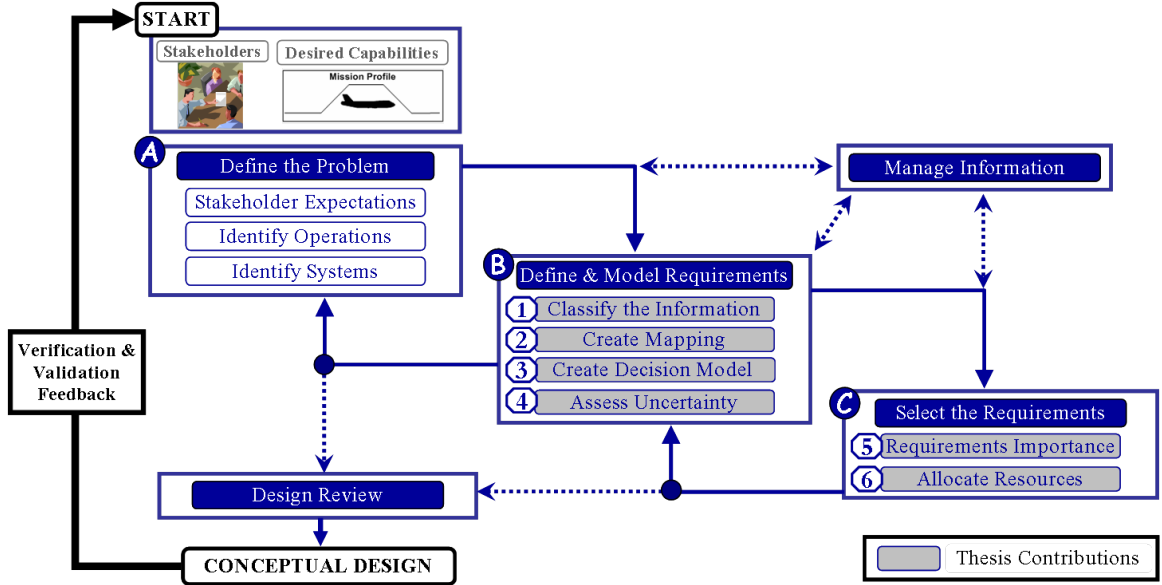


Figure 4.3: Proposed hierarchical requirements methodology.

4.2.1 Step 1: Classify the Information - Requirements Taxonomy

This section describes the proposed requirements taxonomy that is created and used in this research. The first part discusses challenges related to the creation of the taxonomy. The second part describes the specific objectives and attributes of the taxonomy. Finally the third part presents the different levels and taxons, and describes how it is integrated to the methodology.

Requirements Taxonomy Challenges

The requirements taxonomy first comes into play during the problem definition. In sections 3.1 and 3.2 the different types of requirements and taxonomies have been described to understand the current nomenclature. The objective of the requirements taxonomy is to sort through the mass of information coming from stakeholders, historical data, and knowledge databases gathered from previous design projects.

The first challenge is to create and organize the taxons. For taxonomy usefulness, the taxons need to be applicable to a wide variety of aerospace systems, while being specific enough to include the different types of requirements.

Once the taxons are defined, the second challenge is to build the structure of the taxonomy. The objective of the taxonomy’s structure is to provide a logical flow of information to reduce the ambiguity and improve the consistency of the sorted information. As described in the Taxonomy Properties section (3.2.1), the structure should be orthogonal in order to have independent taxons. This property of the taxonomy implies that a requirement can only be stored in one category, and thus reduce the chance of having redundant requirements.

In section 3.2, it has been established that a hierarchical structure is an efficient way to classify and manage the information. The hierarchy starts with general concepts (i.e., user context), and goes into more specific concepts as the level of decomposition increases (i.e., product and process specifications). Since this research is focusing on the conceptual design level, the highest level of the taxonomy should refer to the stakeholders, while the lowest level should provide a transition to preliminary design requirements.

Attributes of the Proposed Taxonomy

The main objective of the proposed taxonomy is to provide a structured approach to identify, classify and manage system requirements. In order to achieve this goal, specific taxonomy attributes have been identified and divided in three categories: taxonomy process, taxonomy structure, and taxonomy content. Table 4.1 lists the desired attributes for each category.

Table 4.1: Attributes of the proposed taxonomy.

Taxonomy Process	Taxonomy Structure	Taxonomy Content
Classify the requirements related information	Based on independent taxons	“Complete”: include the appropriate taxons
Bridge the definition and modeling of requirements	Hierarchical structure - identify the level of requirements	Include all requirement type
Allow the description of both functions and systems		Flexible - can be used by multiple applications
Basis for knowledge based framework		

The general structure of the proposed taxonomy is shown in Figure 4.4. The technical taxons are tailored to aerospace systems, however these taxons could be modified depending

on the type of application. This structure represents the backbone of the requirements classification and management processes. It is divided in six levels, level 1 being the most general to level 6 being the more specific. The second level is inspired from Gershenson & Stauffer (1999) [58], where the only difference lies in the technical taxons.

Also levels 1 and 2 are used as categories to sort the requirements, while levels 3 to 6 are systems dependent and described the requirement types defined in section 3.1. For instance a design requirement defining the number of passengers that a commercial aircraft should carry would be described as follows:

- Specified/Technical-Payload/System [Fuselage]/Functional [Support weight]/ Design [300 passengers]

In this example, the user-context is defined as “Technical/Aerodynamics”, but it could have been an “End-User/Performance” requirement if viewed from the airline company perspective. The third level defines the system, process or operation taxons. Each system, process and operation includes specific requirements that can be further decomposed into levels 4 to 6. The last level of the taxonomy has been defined to include detailed types of conceptual design requirements. At the same time these types of requirements can be used at the beginning of the preliminary design phase. The last topic of this section will discuss the integration of the taxonomy in the conceptual design process.

Taxonomy and Design Process

The requirement definition process starts with information and requirements from the stakeholders. Once in the hand of the design team, the project goes through a series of steps to clarify the problem and identify as many requirements as possible. The next logical step is to create functional and system hierarchies to store the information. Every function must be traced to a requirement, and each function needs a system to perform the desired task; however in some cases there can be multiple systems required to perform unique functions, and an integrated systems can performed multiple functions. For instance, the function “*generate thrust*” requires at the very least a motor and a propeller to achieve this higher

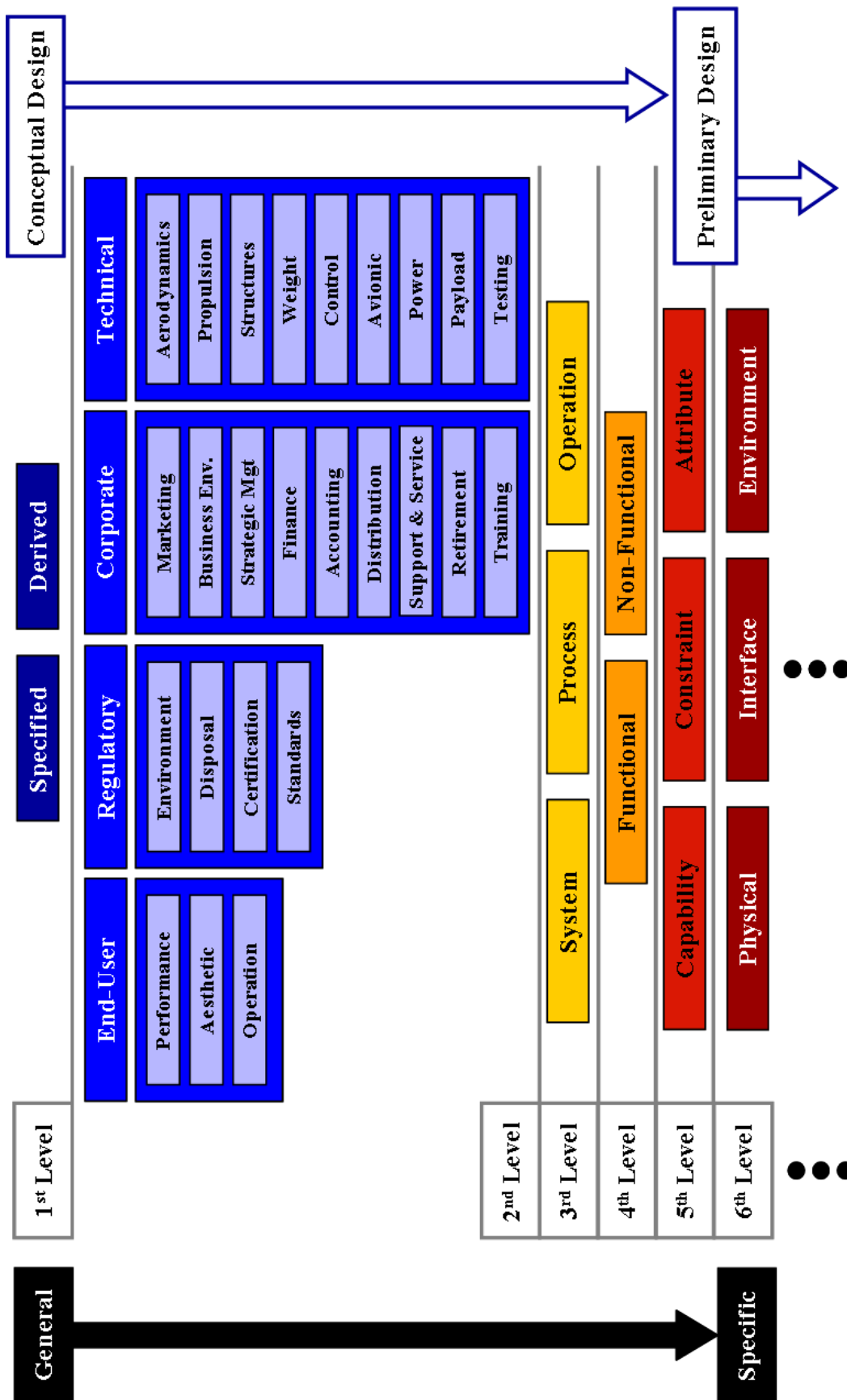


Figure 4.4: Aerospace system requirements taxonomy.

level function, whereas the wing systems can perform multiple functions like “*provide lift*” and “*store energy (i.e., fuel)*”.

Some of the requirements are also derived from the type of systems alternatives considered. For instance if the propulsion system includes a motor-propeller instead of a turbine engine, then some requirements will be specific to the motor-propeller system (i.e., operating conditions).

In order to maximize the design freedom in conceptual design, it is important to start by listing as many alternatives as possible. Each alternative provides more information and knowledge about the project, which ultimately leads to a large pool of requirements. Once the requirements are identified, they must be classified in a framework that enables their easy access and management. This framework is the requirements taxonomy.

By iterating between the problem definition and the requirements taxonomy, new requirements may be identified, defined and classified in the process. Once the time and budget for this task are depleted, the design team must determine which requirements are the most important for the success of the project, and how to allocate the resources to satisfy them. To achieve this goal, the design team needs to acquire more information about the impact of the requirements on the system. This leads to the second task of the proposed methodology, the creation of the requirements mapping.

This section defines the proposed requirements taxonomy. It describes how the taxonomy is integrated in the design process, the taxonomy structure with the flow of information, and the different levels and types of requirements included in the taxonomy content. It is also important to reiterate on few key points. First the requirements taxonomy is not part of a sequential process but part of an iterative process between the requirement definition, modeling and selection. Second, the taxonomy must evolve with the system, and new requirements can be added at any time during the design process. Finally, as the requirements are classified in the taxonomy, the designer must take the extra time to make sure that the requirements are satisfying the traceability and consistency properties (section 2.1.2.1).

4.2.2 Step 2: Create the Mapping -Hierarchical and Network Model

While the information defining the problem is gathered and sorted in Step 1, the objective of Step 2 is to create a structured mapping that will assure the traceability between the stakeholder expectations and the systems alternatives.

The elements required to create the mapping are defined in the NASA systems engineering process, section 2.3.4, more specifically the stakeholder expectations definition and the technical requirements definition processes. Figure 4.5 schematically illustrates how the functions and measures of effectiveness are flowing from the stakeholder expectations to the operations and systems.

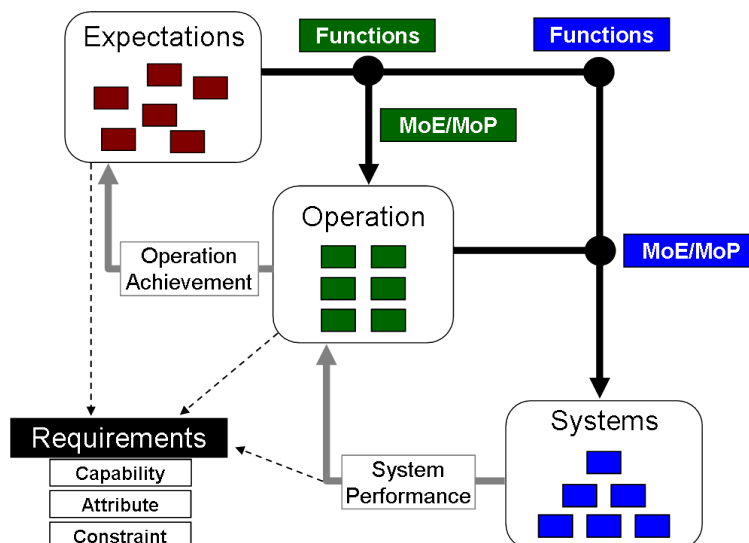


Figure 4.5: Elements needed in initial requirements mapping.

The mapping starts with the stakeholder expectations defined as an “*actor-verb-object*” statement. With these expectations, the second activity is to define the operational and systems functions. The operational functions are defined from the concept of operations (CONOPS), while the systems functions come from the systems architecture (i.e., airframe, propulsion, power, etc.). INCOSE defines the CONOPS as the description of “*the way the system works from the operator’s perspective*” [83]. For the UAV experiment, the CONOPS is represented by the hurricane tracker UAV mission profile.

Based on the CONOPS and systems functions, the design team can list specific measures of effectiveness (i.e., weight, strength, modularity, etc.) require to achieve the expectations.

Consequently, the final activity is to regroup these elements into a well formed requirements statement including a capability (expectation or function), attributes (MoE or MoP) and if needed, constraints (operational or physical).

An example of an operational function is “*the aircraft orbits over a target area*”. For this function the “*time on station*” and “*endurance altitude*” are examples of measures of effectiveness. On the systems side, for the propulsion system an example of the function is “*energy is converted into mechanical work*” with the “*propulsion thrust*” and “*energy consumption*” as MoEs.

The key activity becomes to combine these functions and MoEs into hierarchical or network mapping. This can be accomplished using a top-down and bottom-up approach as illustrated in Figure 4.6. Ultimately the success of the project will depend on how well the system is performing within the concept of operations, hence the importance of the operational scenario to start the mapping.

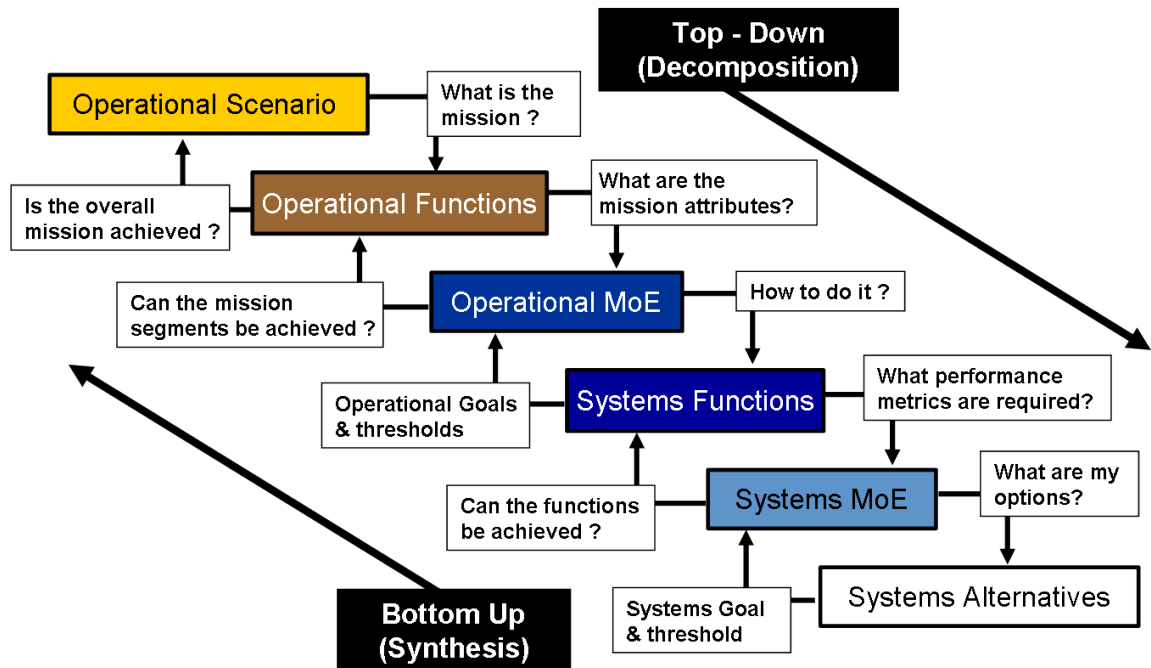


Figure 4.6: Top-down and bottom-up mapping.

As the mapping is transitioning from the operational to the systems platform, the focus is shifted from “*what is the purpose?*” to “*how to accomplish it?*”. The system’s functions are then defined through a set of MoEs, which themselves often depend on the types of

system alternatives considered by the design team. There are two general categories of system alternatives, existing and new alternatives. Either existing alternatives are used to meet the MoEs or new systems need to be designed and manufactured to meet the MoEs and expectations. In either case, the systems alternatives are more than likely to influence the achievement of the systems functions and consequently the concept of operations. This is one reason justifying the need to incorporate the systems alternatives in the requirements mapping process.

Figure 4.7 illustrates the differences between a commonly used requirements mapping approach and this research proposed methodology.

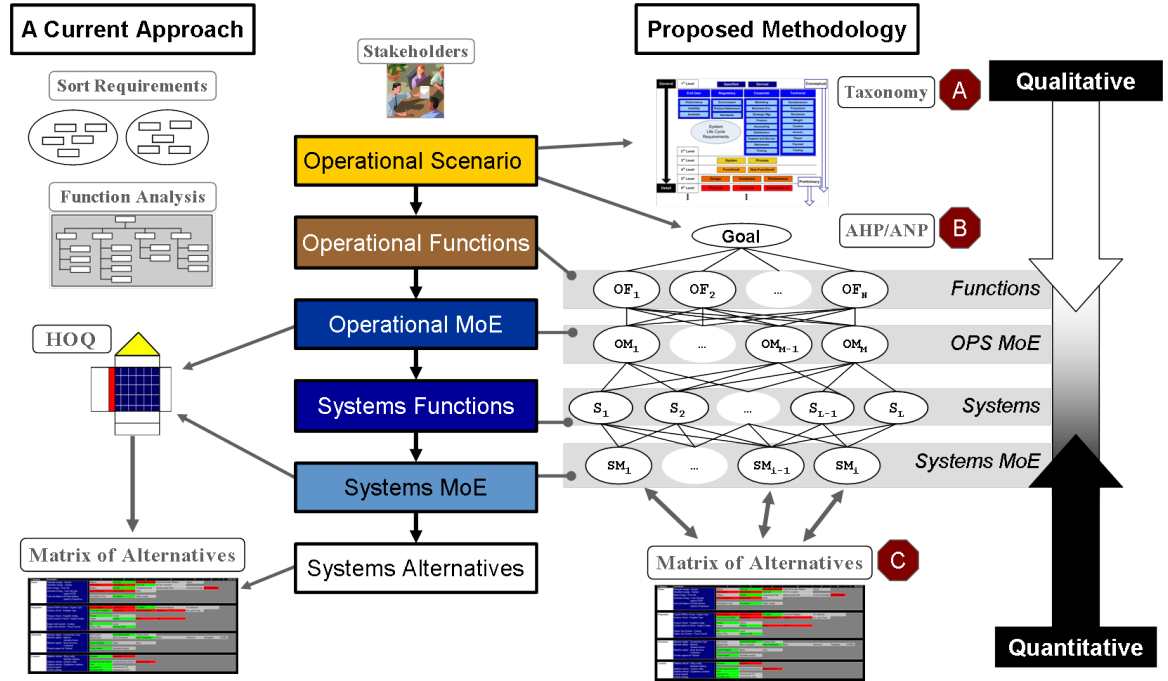


Figure 4.7: Steps involved in the requirements mapping.

It can be seen that the current approach is sequential and that the flow of information is unidirectional. The information is first sorted and classified by affinity, then the mapping between the requirements and systems characteristics is performed within the house of quality. The result of the house of quality provides an indication of the most important engineering characteristics, which are subsequently used as bases to brainstorm alternatives.

In the proposed methodology, the information is gathered and classified using the taxonomy (Step 1), and then all the major elements (functions and MoEs) are used in the mapping

using AHP/ANP. This mapping is bi-directional since the lower levels of the mapping influence the higher levels. Furthermore, the analysis of alternatives directly interacts with the systems MoEs, and at this level the design team can take advantage of available quantitative information. Therefore, quantitative information can be used within the mapping model through the lower levels of the framework.

It is to be noted that in the current approach the house of quality also includes quantitative information, however this information is taken more as a reference and does not directly influence the higher levels of the mapping.

To summarize Step 2, here are the specific activities that are involved in the creation of the mapping:

- A) Gather stakeholder expectations and use the taxonomy to classify the information;
- B) Divide the expectations in terms of concept of operations and systems architecture;
- C) For both systems architecture and CONOPS, brainstorm to identify functions and measures of effectiveness;
- D) Create the hierarchical mapping structuring the operations and systems functions and MoEs using ANP (Figure 4.7);
- E) Brainstorm to identify systems alternatives and map them to the MoEs that they influence;
- F) Structure the systems alternatives in a matrix of alternatives (morphological matrix).

4.2.3 Step 3: Create the Decision Model - Pairwise Comparisons

The creation of the decision model consists of performing the pairwise comparisons resulting from the mapping established in Step 2. During the conceptual design, the design team is more than likely to populate the decision model, however nothing prevents the team from asking experts and decision makers to help in the process. This can be done with a survey or during focus groups. This section describes the different activities involved in the creation of the decision model through pairwise comparisons.

In this research two tools are used to perform the pairwise comparisons: SuperDecisions created by the ANP Team [167], and Microsoft Excel^(R) based AHP tools created by the author. SuperDecisions is an object oriented tool that allows the creation of hierarchies, networks, and the evaluation of the limit matrix. The Excel based tool is used to perform

pairwise comparisons and can integrate the priority results from SuperDecisions with the uncertainty analysis approach.

A simple hierarchy example is used to describe the activities involved in the creation of the decision model. This hierarchy has been created in SuperDecisions and includes two criteria linked with four alternatives, as shown in Figure 4.8.

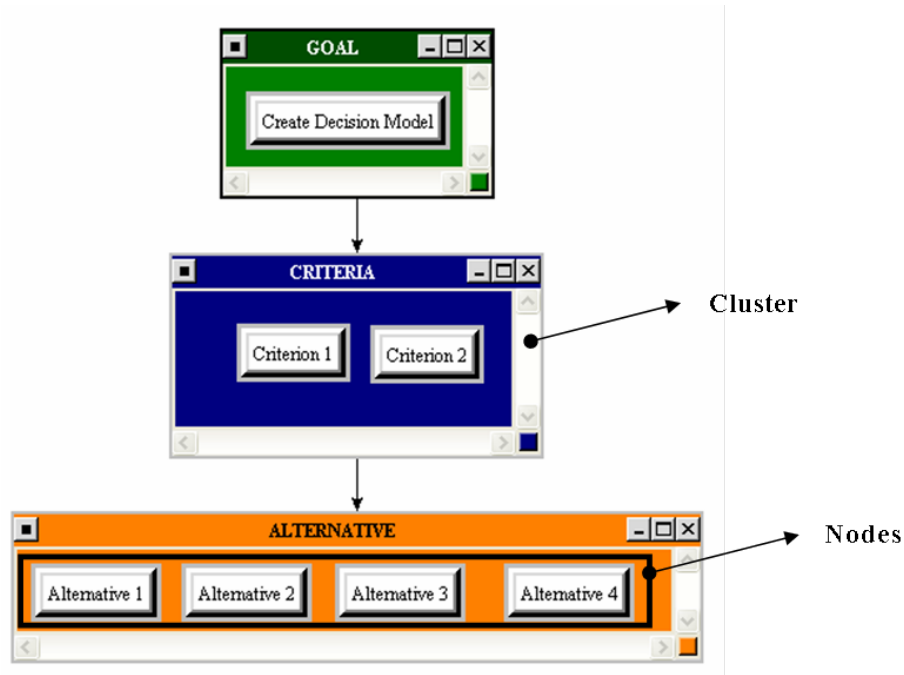


Figure 4.8: Example: Decision model.

In SuperDecisions, the user needs to create clusters and then populates the clusters with node elements. The clusters represent the different level included in the hierarchy. The software allows the user to create connexions between the nodes, which correspond to the mapping process of Step 2. The different connexions can be visualized in a matrix called *unweighted matrix*, where the results of the pairwise comparisons will later be stored. Figure 4.9 illustrates the unweighted matrix for the example of Figure 4.8.

In the unweighted matrix, the directionality of the connexion starts *from* the columns *to* the rows. For instance there are two connexions starting from the goal to Criterion 1 and Criterion 2. At this time, no preference has been input into the model, consequently the preferences are equally important. Also note that the summation of the nodes within each column is equal to one.

	Goal	Crit. 1	Crit. 2	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Goal	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Criterion 1	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Criterion 2	0.50000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Alternative 1	0.00000	0.25000	0.25000	0.00000	0.00000	0.00000	0.00000
Alternative 2	0.00000	0.25000	0.25000	0.00000	0.00000	0.00000	0.00000
Alternative 3	0.00000	0.25000	0.25000	0.00000	0.00000	0.00000	0.00000
Alternative 4	0.00000	0.25000	0.25000	0.00000	0.00000	0.00000	0.00000

Figure 4.9: Example of unweighted matrix.

The next steps are to perform the pairwise comparisons, check the consistency and synthesize the priorities. For this example the user would have to define: (1) which criteria is more important, (2) the relative importance of the alternatives with respect to criterion 1, (3) the relative importance of the alternatives with respect to criterion 2. In this case, the user has to perform 13 pairwise comparisons. For complex systems, one can expect to perform a large number of pairwise comparisons. An approach that can be used to reduce the number of comparisons is to focus on the primary comparisons, as illustrated in Figure 4.10.

Number of Selection Criteria		1																	Number of Primary		3
Number of Pairwise Comparison		6																	Consistency +/-		0.9
Number of Criteria		4																	Alternative 2		Consistent
Selection	Alternative 1																		Alternative 2		Primary
1	Criteria 2	Alternative 1		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
2	Criteria 2	Alternative 1		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
3	Criteria 2	Alternative 1		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
4	Criteria 2	Alternative 2		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
5	Criteria 2	Alternative 2		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	
6	Criteria 2	Alternative 3		9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	

Figure 4.10: Primary comparisons with the Excel interface.

Due to the structure of the pairwise comparison, a “*perfectly*” consistent decision model does not require the user to perform all the comparisons. As shown in Figure 4.10, one can identify the primary comparisons and from them infer the other comparisons. For instance, by comparing Alt. 1 vs. Alt. 2, and Alt. 2 vs. Alt. 3, one can infer the preferences between Alt. 1 vs. Alt. 3. Even though, this approach can be used to accelerate the process, it is still recommended to perform all the comparisons in order to identify potential contradictions within the team’s preferences. Figure 4.11 presents how the pairwise comparisons are performed in the SuperDecisions software.

While performing the pairwise comparisons, it is important to always be aware of the

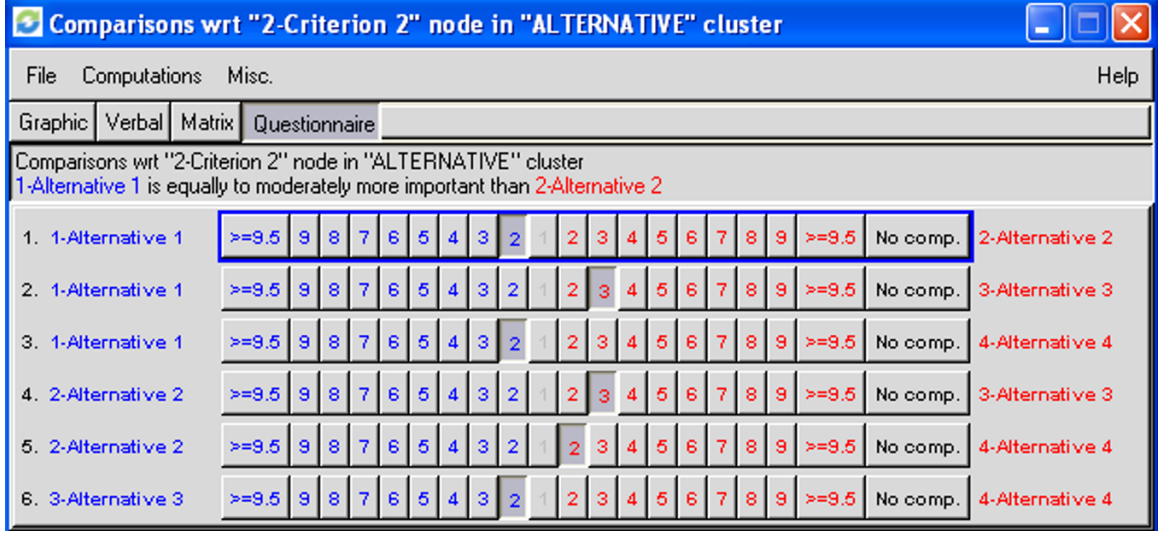


Figure 4.11: Pairwise comparisons in SuperDecisions.

context. For instance in Figure 4.11, one can notice that the context is clearly stated: “*Comparison with respect to **Criterion 2** in the **Alternative** cluster, **Alternative 1** is equally to moderately more important than **Alternative 2**.*” The knowledge of the comparison context is essential in a hierarchical or network structure, since the current level impacts the level above and below.

Once the comparisons are completed, the users can instantaneously verify the priorities of the alternatives with respect to the criterion, and at the same time check the consistency of the comparisons, see Figure 4.12. If the consistency index is greater than 0.1 to 0.2, then the user must try to understand where the inconsistency is coming from. Doing a consistency check can generate some discussions within the team (improve team work) and also shed light on some misconceptions of the problem.

Once the user has established the (1) relative importance of the criteria with respect to the goal and (2) the relative importance of the alternatives with respect to the criteria; the final step is to synthesize the entire hierarchy (bottom-up process), see Figure 4.13. During the synthesis process, all the priorities are stored in the supermatrix, and the synthesized results are calculated by taking the limit of the matrix as explained in section 3.3.4.

From this example, it can be seen that for a hierarchical decision model, the synthesis of the results are equivalent to the desirability index of Eq.(3.12):

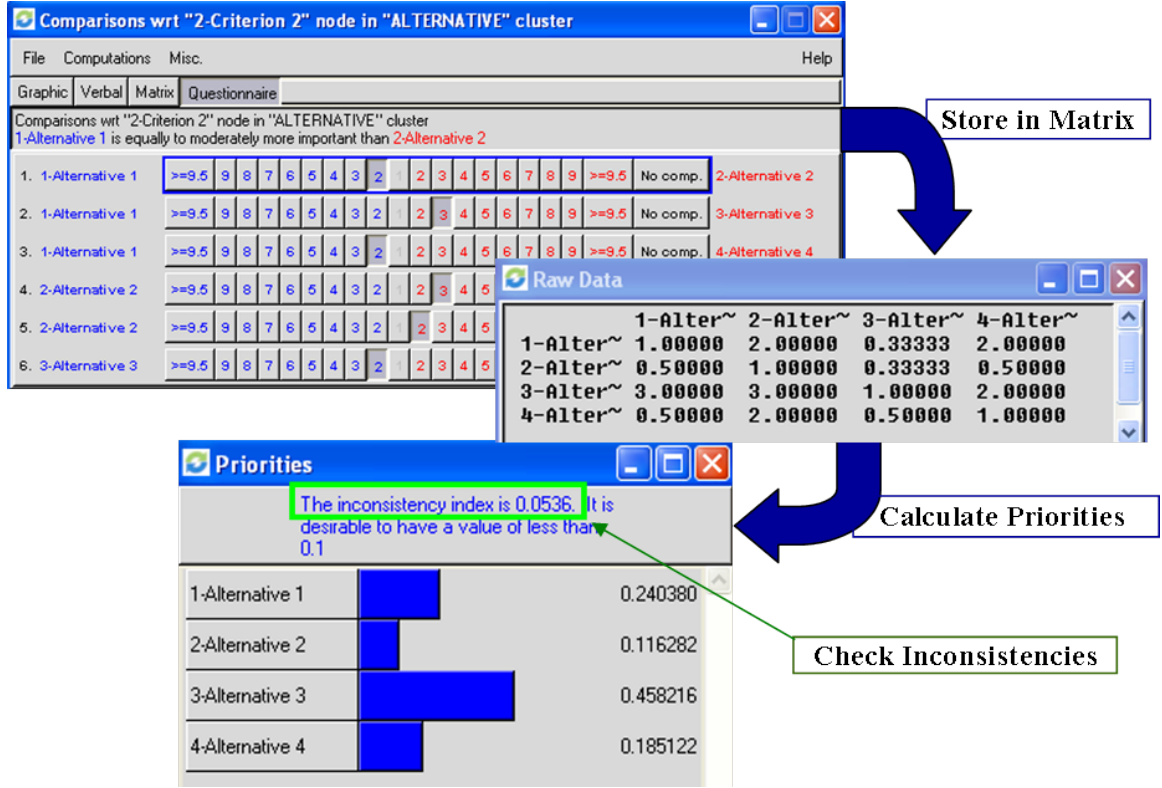


Figure 4.12: Priorities and inconsistency check.

$$\text{Synthesize Alt.1} : w_{C_1} \times [W_{A_1}]_{C_1} + w_{C_2} \times [W_{A_1}]_2 = 0.167 \times 0.472 + 0.333 \times 0.240 = 0.159$$

In SuperDecisions, the results of the synthesis process correspond to the “Raw” values of Figure 4.13. The “Ideals” and “Normals” values are respectively obtained from an infinite and L1-norms of the “Raw” values, as given in Eq. 4.1.

$$\begin{aligned} \text{Given :} \quad & \vec{x} = [x_1, x_2, \dots, x_n] \\ \text{Infinity norm :} \quad & \|\vec{x}\|_{\infty} = \max_i |x_i| \quad i = 1, \dots, n \\ \text{L1 norm :} \quad & \|\vec{x}\|_1 = \sum_{i=1}^n |x_i| \quad i = 1, \dots, n \end{aligned} \quad (4.1)$$

To summarize Step 3, here are the activities involved in the creation of the decision model:

- A) Perform pairwise comparisons (clusters and nodes);
- B) Check the consistency of the preferences for each group of comparison;
- C) Synthesize the relative importance of the alternatives.

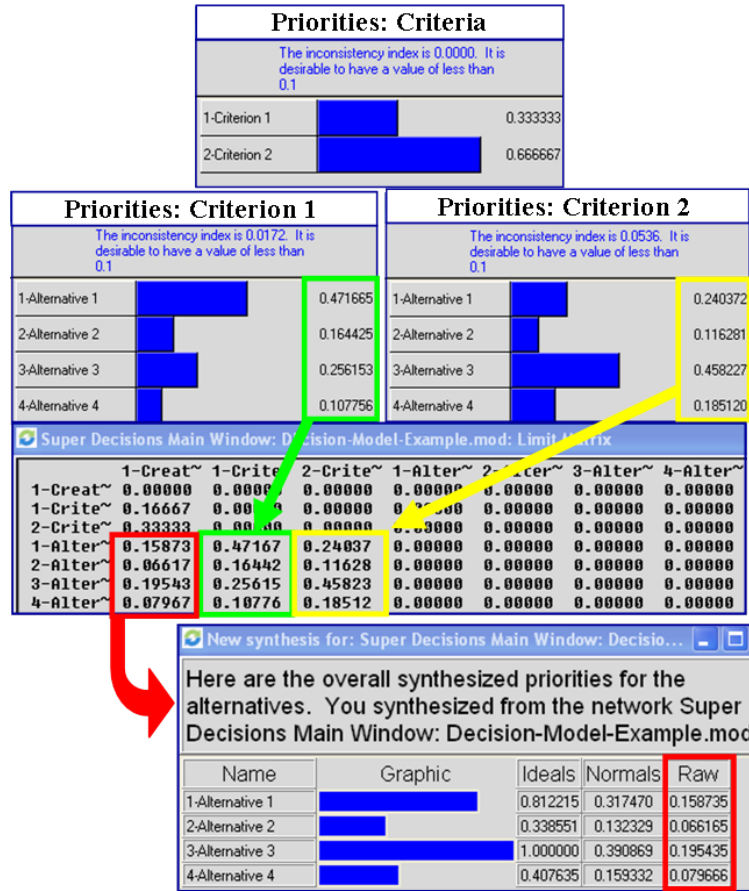


Figure 4.13: Synthesis of the hierarchy.

4.2.4 Step 4: Assess the Uncertainty

Two methods were described in section 3.4 to assess and propagate the epistemic uncertainty within the decision model: sensitivity analysis and Monte Carlo methods. The objective of this section is to describe how these approaches can be integrated with steps 2 & 3.

The software SuperDecisions includes a sensitivity analysis feature that can be used to evaluate the variability of the overall priorities as a function of any components of the hierarchical model. As an example, Figure 4.14 shows the sensitivity analysis results taken from the simple hierarchical model of Step 3.

In this sensitivity analysis figure, the x -axis represents the relative importance of Criterion 1 and the y -axis represents the synthesis value of the alternatives. It can be observed that when Criterion 1 is lower than 0.5 Alternative 3 has the highest overall importance,

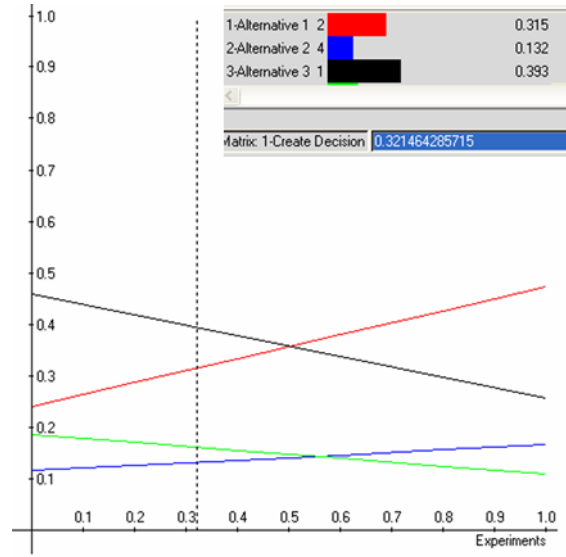


Figure 4.14: Sensitivity analysis of the alternatives by varying the criterion 1 importance.

whereas when Criterion 1 is greater than 0.5 Alternative 1 has the highest overall importance. It is to be noted that the relative importance of the two criteria are dependent since their sum must be equaled to 1 ($Criterion\ 1 + Criterion\ 2 = 1$). This constraint comes from the pairwise comparison priorities of the criteria.

With this interactive sensitivity analysis feature, the design team can exercise “*what if*” scenarios and visualize how the ranking of the alternatives is changing as a function of the relative importance of the criteria. As the number of criteria increases, it requires more than one figure to visualize the variability of the overall priorities, since only two criteria can be varied at the time with a two dimensional graph. Figure 4.15 illustrates an algorithm that can be used to create multiple sensitivity analysis figures based on three selection criteria.

The other uncertainty analysis technique is based on Monte Carlo methods. The application of the Monte Carlo methods was discussed in section 3.4.2. It was established that this approach is flexible (integration), handles large uncertainty, and is simple to use. Monte Carlo methods are not embedded in the SuperDecisions software, but the results from the limit matrix can be easily synthesized in Microsoft Excel. Therefore, a framework needs to be created to integrate the Monte Carlo methods with the results of the decision model.

This framework has to enable the user to select the range of the random number distributions, propagate the uncertainty within the decision model, and calculate the PDFs and

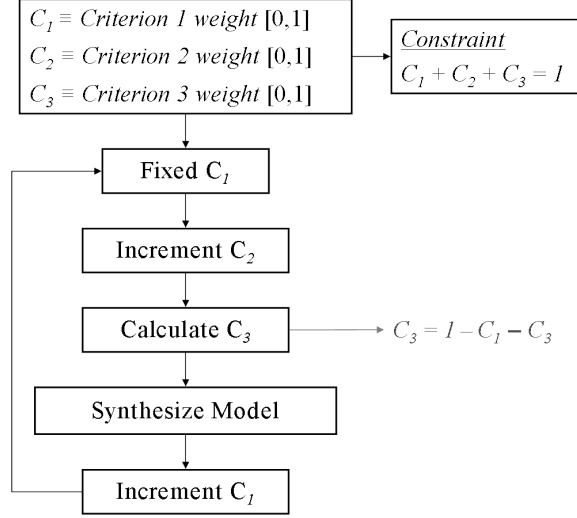


Figure 4.15: Sensitivity analysis algorithm for three criteria.

CDFs. This process is illustrated in Figure 4.16.

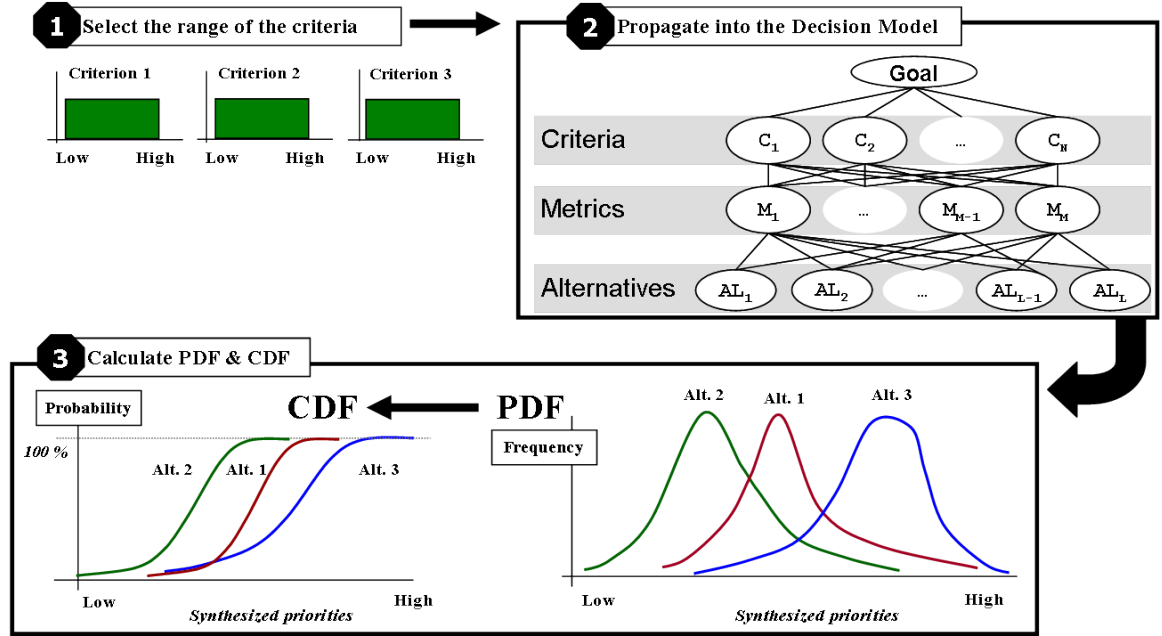


Figure 4.16: Propagation of epistemic uncertainty with Monte Carlo methods.

Since the value of the criteria are dependent on each other, an algorithm has to be created following the logic shown in Figure 4.17.

This algorithm assumes a Uniform Distribution (UD) of the criteria in order to explore as much as the uncertainty space as possible. In Figure 4.17, the variables X and Y correspond to the random number picked within the UD to represent the criteria. Then the algorithm

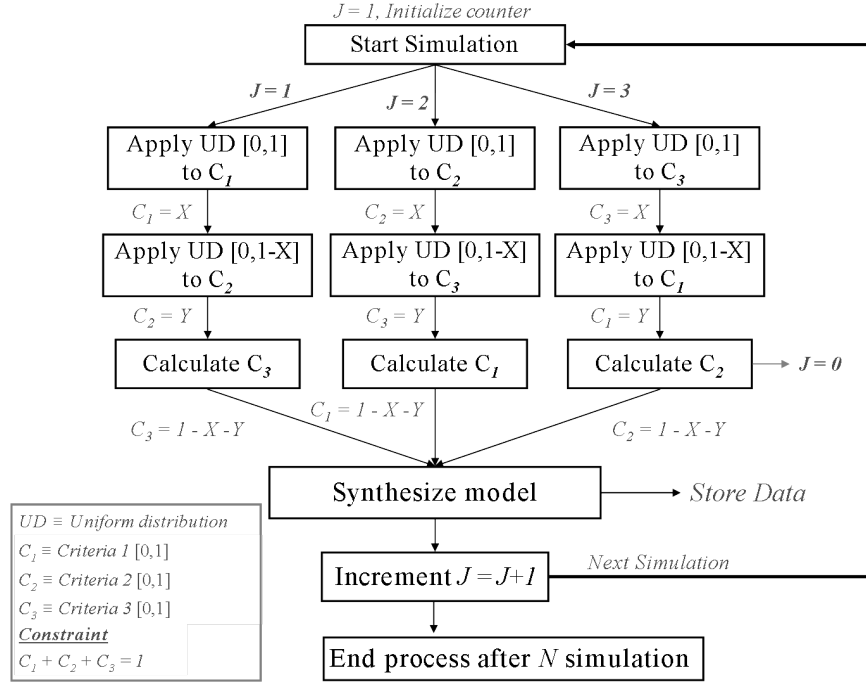


Figure 4.17: Monte Carlo algorithm for three criteria.

synthesizes the priorities of the decision model and stores the data. The user needs to specify a desired number of simulations (N), depending on the time available and the uncertainty surrounding the criteria.

To summarize Step 4, here are the activities involved in the analysis and propagation of epistemic uncertainty:

- A) Identify the major assumptions;
- B) Select a range of values for the random variables (relative importance);
- C) Propagate uncertainty:
 - i. Generate data for the sensitivity analysis;
 - ii. Perform Monte Carlo simulations;
- D) Synthesize the decision models;
- E) Visualize the variability of the responses;
 - i. Create sensitivity analysis graphs;
 - ii. Monte Carlo: Calculate PDFs and CDFs.

4.2.5 Step 5: Requirements Importance

The evaluation of the requirements importance is based on the stakeholder's down-selection criteria. As discussed in section 3.5, there must be lower-level criteria as well as top-level criteria to down-select the number of requirements. The Benefits-Opportunities-Costs-Risks (BOCR) were described as top-level criteria frequently integrated with the AHP/ANP process. The objective of this section is to determine where in the hierarchical structure to integrate the BOCR criteria.

The benefits, costs and risks of a system are often referring to a specific system alternative. Therefore, a logical level to integrate these criteria in the requirements mapping would be between the systems MoEs and the systems alternatives, as illustrated in Figure 4.18.

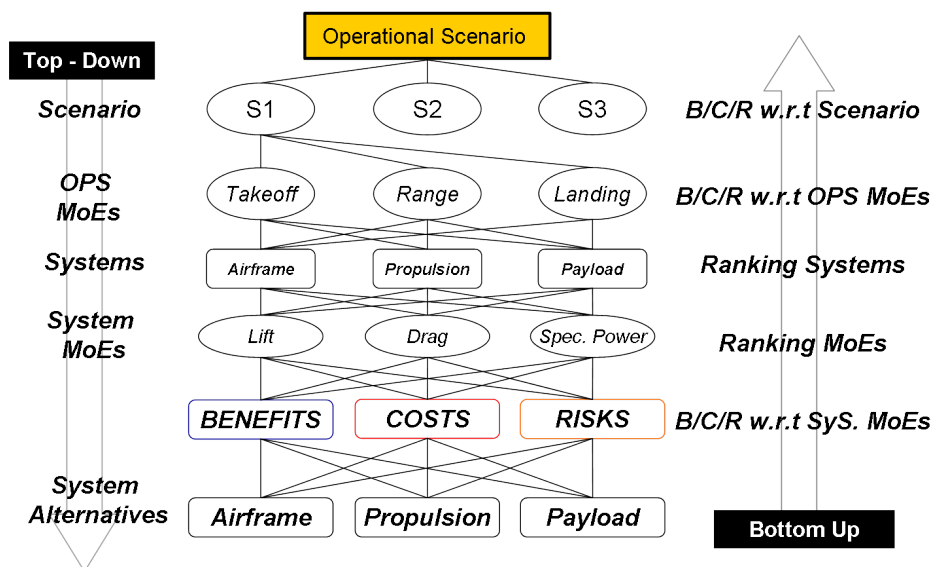


Figure 4.18: Integration of Benefits, Costs and Risks to the mapping.

The levels above the benefits, costs and risks do not specifically depend on the systems alternatives, however the relative importance of the higher level elements should influence which systems alternatives are preferred to achieve the mission. Figure 4.19 shows how the relative importance of the higher level elements can be combined with the BOCR criteria of the decision model.

To use the mapping of Figure 4.19, first the user has to identify the alternatives influencing each system MoE. In that context, the *Benefits* can be defined in terms of performance,

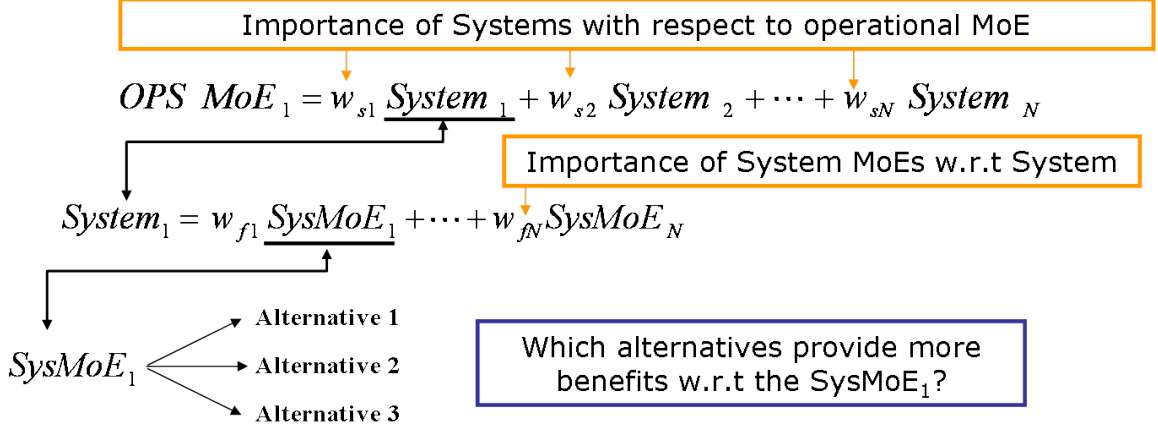


Figure 4.19: BOCR mapping to alternatives.

implying that better performance is translated into higher benefits in the achievement of the mission. The *Costs* criterion can then use historical data to estimate the cost of each system, while the *Risks* criterion can be divided into sub-criteria like complexity, safety, and growth factor.

It is important to note that at this stage there is more quantitative information that could be directly added to the decision model. For instance, assuming that one of the systems MoE is engine mass, and that the masses of the alternatives are known from historical data; it is possible to determine the relative benefits of the alternatives with respect to system mass as follows (with smaller mass the better):

Mass(kg)	Ratio	Ideal Value	Normalized Value
$Alt_1 = 50$	$\frac{50\ kg}{50\ kg}$	1.000	0.487
$Alt_2 = 80$	$\frac{50\ kg}{80\ kg}$	0.625	0.303
$Alt_3 = 110$	$\frac{50\ kg}{110\ kg}$	0.455	0.220

To combine the relative benefits with the decision model, the normalized values need to be used in order to match the AHP/ANP structure. Consequently these priorities can be mapped with the systems mass and depending on the importance of this MoE the benefits provided by the alternatives will vary.

To summarize Step 5, here are the activities involved in the analysis and propagation of

epistemic uncertainty:

- A) Determine which BOCR dimensions to consider;
- B) Map the decision model (System MoEs) to the desired dimensions;
- C) Perform pairwise comparisons;
 - i. Use quantitative data if available;
- D) Synthesize the overall results;

For this step, the synthesis of the results can be visualized by creating a ranking of the elements per level. In the presence of uncertainty, this ranking can be accomplished based on a probability of success from the CDF curves. The final step is then to use these results to allocate the available resources.

4.2.6 Step 6: Ranking and Resource Allocation

This step is meant to close the requirements methodology by creating the requirements statements, and allocating the resources required for the systems design. Based on the synthesized results from Step 5, the design team can create a ranking of the systems MoEs, systems, and operational MoEs. These rankings can either be represented with deterministic or stochastic figures depending on the user preference and the amount of epistemic uncertainty.

With the information provided from the Benefits-Costs-Risks model, the user can list the types of resources required for the project (i.e., monetary, time, technology, etc.). As discussed in Ref. [159], it is possible to use tangible resources information to estimate the value of intangible resources like public image, quality, and safety. By combining both types of information, the design team can then calculate the total amount of tangible resources required for the project.

To summarize Step 6, here are the activities involved in the analysis and propagation of epistemic uncertainty:

- A) Create ranking;
 - i. Systems MoEs;
 - ii. Systems;
 - iii. Operational MoEs;

- B) Create requirement statements;
- C) Define the types of resources required;
- D) Allocate resources to most important requirements or estimate the project required resources.

4.3 Summary of Proposed Methodology Activities

Figure 4.20 presents a summary of the proposed methodology activities.

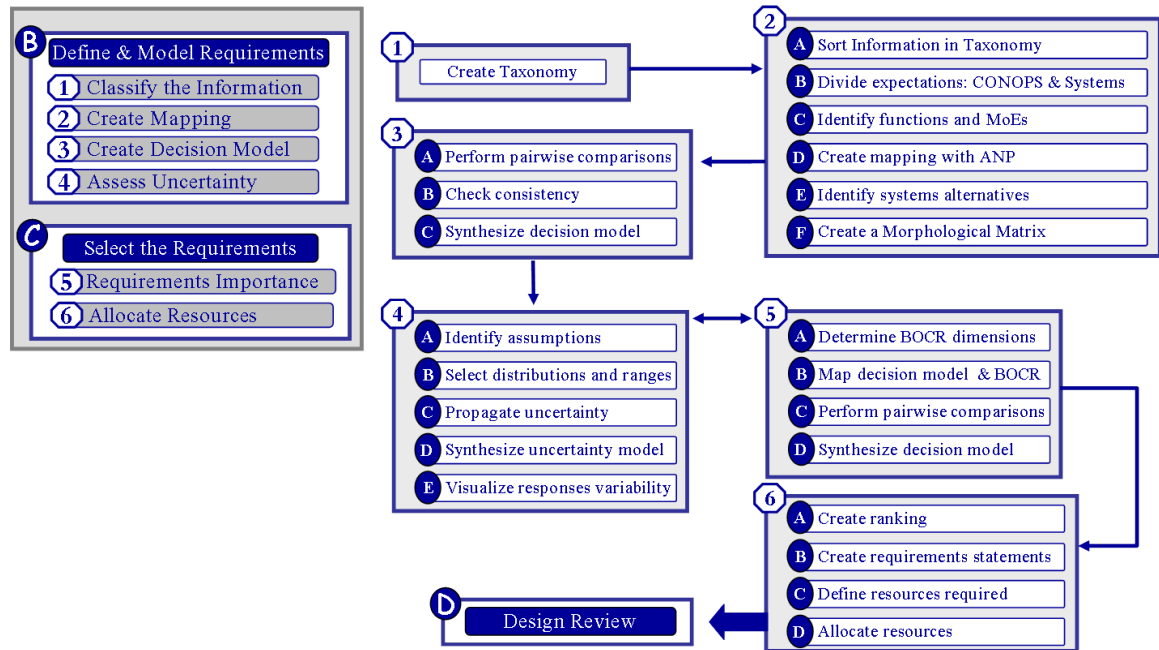


Figure 4.20: Summary of the proposed methodology activities

Chapter V

IMPLEMENTATION OF PROPOSED METHODOLOGY

The proposed methodology described in Chapter 4 is applied to two experiments in this chapter. The objective of these experiments is to try to answer the research questions by using the hypotheses proposed in section 4.1.

The first experiment applies part of the proposed methodology to the definition and modeling of a subjective requirement. In this experiment, different decision model synthesis techniques are applied to the requirements mapping, and also both the sensitivity analysis and Monte Carlo methods are tested to evaluate their potential application to a more complex design problem.

The second experiment applies the six steps of the proposed methodology to the design of a Hurricane Tracker UAV. Through this example application one can follow the traceability of the information from the stakeholder expectations to the systems alternatives.

5.1 First Experiment: Defining and Modeling a Subjective Requirement

The goal of this experiment is not to perform the complete requirements analysis, but to demonstrate the ability of the proposed methodology to define and model a subjective requirement through hierarchical mapping. This experiment refers to the Research Questions and Hypotheses illustrated in Figure 5.1. This figure also shows the relationship between the research questions, hypotheses and the steps involved in the definition and modeling of the proposed methodology.

One of the objectives of the methodology is to be able to model both quantitative and qualitative requirements. On one hand, quantitative requirements like range and endurance are commonly defined and modeled in systems engineering. On the other hand, qualitative or subjective requirements are often project specific and their relationships with the systems

are often ambiguous. For this reason, this experiment focuses on the definition and modeling of a subjective requirement, and the lessons learned from this experiment will be applied to the UAV design problem.

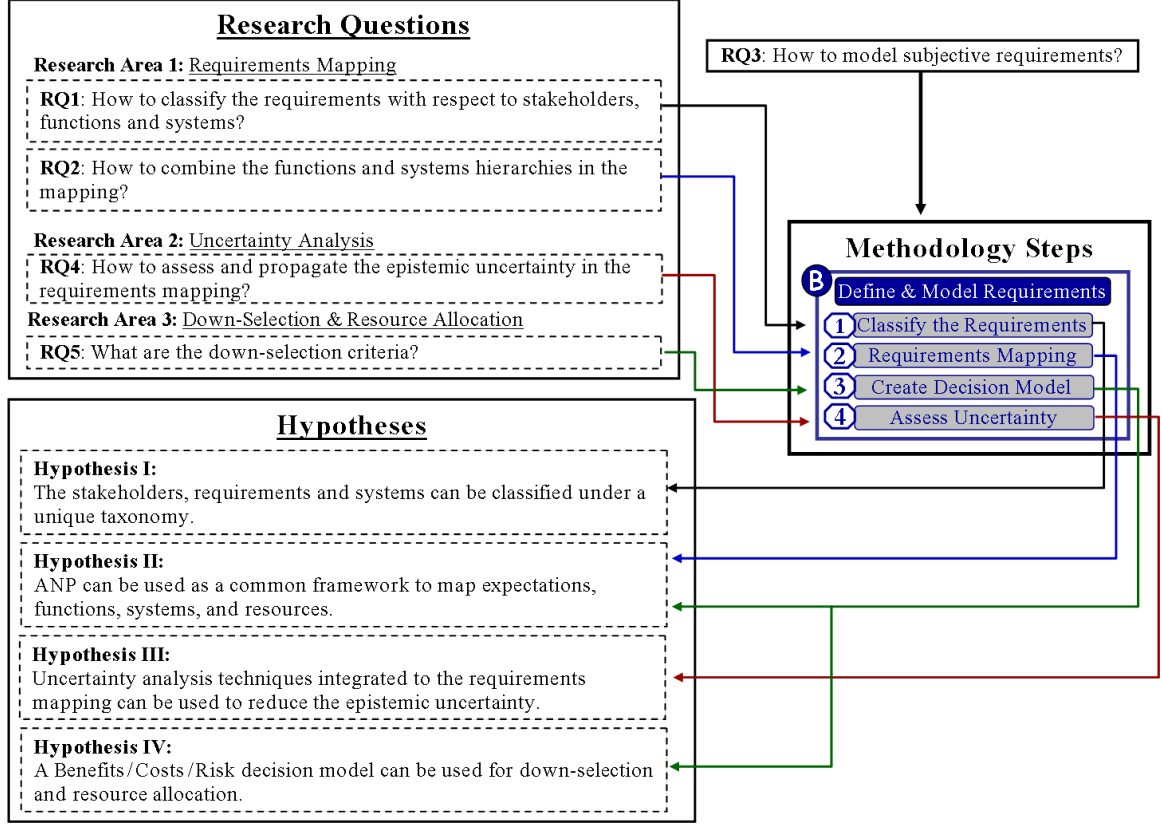


Figure 5.1: Experiment: Defining and Modeling Requirements

5.2 The Presidential Helicopter Experiment

In January 2005, the U.S. Navy awarded the new Presidential helicopter program to the Lockheed Martin Corporation as prime contractor. The \$6.1 billion project consists of replacing the current Marine One fleet of Sikorsky VH-3 Sea Kings with 23 VH-71 aircraft[31].

Marine One is said to be one of the most photographed helicopters in the world. Carrying the President of the United States of America, this new helicopter needs to project to the American public and the world a certain prestige. Assuming this expectation from the U.S. Navy and ultimately from the White House, this helicopter should look presidential. This requirement, “**looking presidential**”, is a qualitative and subjective requirement that has

interesting impacts on the design of the helicopter. This section described in detail how the proposed methodology can be used to define and model such a requirement.

The first part describes how the requirement taxonomy is used to classify and define the requirement. The second part describes the mapping between the requirement, the operation and system level characteristics. The third part describes the survey that was created to model satisfaction of the requirement. The last part of this experiment describes the creation of a hierarchical decision model to assess the impact of the stakeholder selection on the overall benefit and cost of the requirement.

5.2.1 Classification, Definition and Mapping of the Requirement

Starting with the following requirement statement:

The new Marine One helicopter shall look presidential.

The first step consists of listing the stakeholders. It is possible to list and categorize the stakeholders following the second level of the requirement taxonomy, established in section 4.2, as depicted in Table 5.1. This list is specifically tailored for this experiment’s requirement and represents only a sub-set of the stakeholders involved in the presidential helicopter conceptual design; for instance the FAA and the U.S. Navy (Mil. Std) would need to be added under the regulatory category.

Table 5.1: Presidential helicopter stakeholders.

End-User	Corporate	Technical
White House	Lockheed Martin	Lockheed Martin
American Public	Team U.S. 101	Design Team
U.S. Navy		
Navy Pilot		

A notional flow-down of the impact of the requirement on the stakeholders and systems is shown in Figure 5.2. This figure illustrates the hierarchy in the satisfaction of the requirement “*looking presidential*”. First, the American public needs to be satisfied because the new vehicle is built with their taxes, and projects the image of the country while carrying the President. Then, assuming that the preferences of the American public have an

impact on the helicopter’s configuration, it would be important to know the influence of these preferences on the other stakeholders, White House and manufacturer, and the vehicle itself.

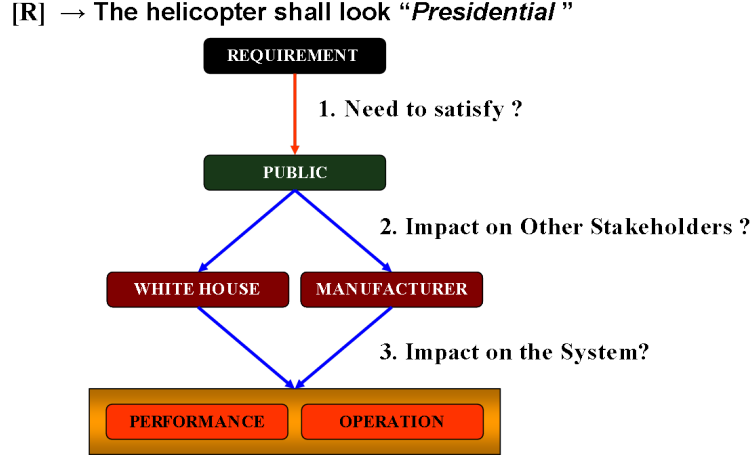


Figure 5.2: Stakeholders relationships flow-down.

The first step that needs to be taken to understand this requirement is to define the components of the helicopter influencing the presidential appearance, and subsequently define the preferences of the American public with respect to these components. In the proposed methodology, the mapping between requirements, stakeholders and systems is achieved through the requirement taxonomy, as shown in Figure 5.3.

Under the *End-User* category, the vehicle *aesthetics* and *operations* have been identified to potentially impact the requirement. In the *Technical* category the shape of the airframe may also impact the appearance of the vehicle, as is the case for automobiles. Consequently the requirement “looking presidential” can be defined as a function of the vehicle shape, aesthetics and protocol as follows:

$$R_1 = f(Shape, Aesthetics, Protocol) \quad (5.1)$$

To validate this definition with the American public, a survey needs to be created and distributed to a sample of the population. The survey is meant to answer two objectives: (1) to verify if the components shape, aesthetics and protocol influence the appearance of the vehicle, and (2) to determine which vehicle alternatives for each of the shape, aesthetics

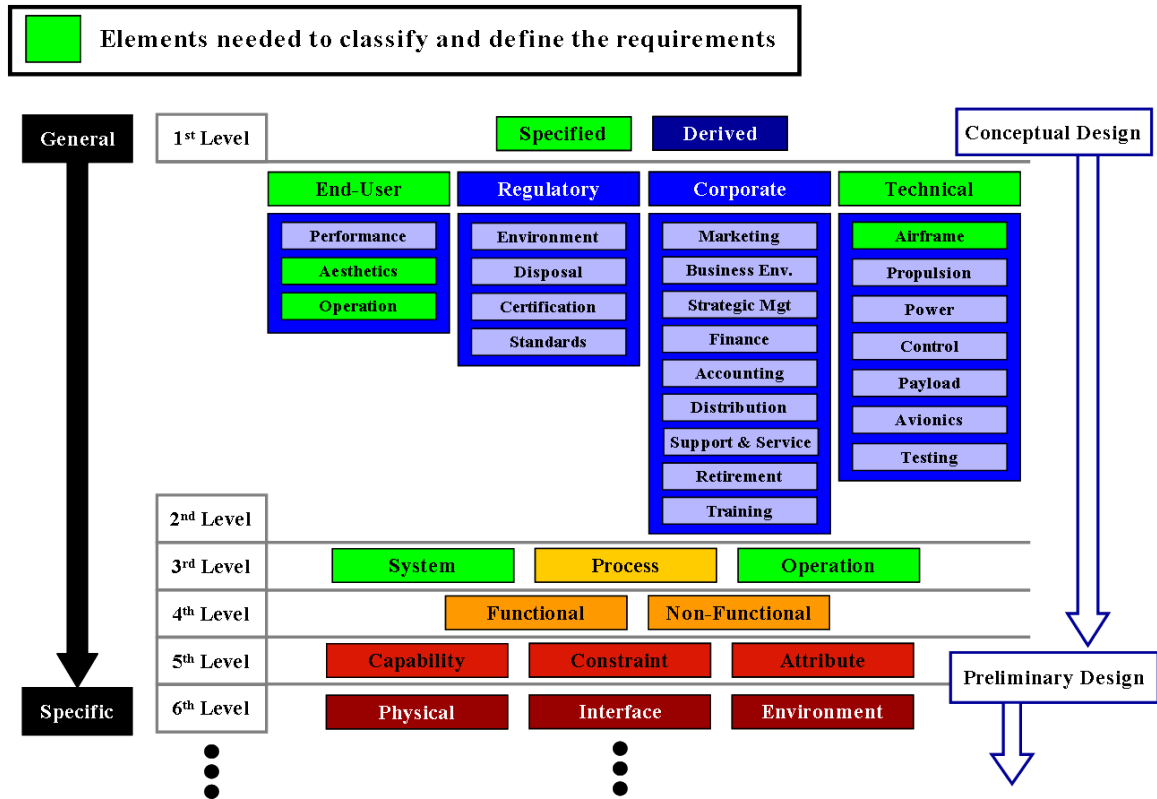


Figure 5.3: Classify and define “looking presidential”.

and protocol components are preferred by the participants.

At this point many alternatives could have been defined and exposed to the participants, however the goal of this experiment is to establish the framework for the proposed methodology and learn from this initial experiment, and not to redesign the presidential helicopter. Therefore, a set of alternatives was created and included in a survey to establish the preferences of the American public, and thus creating a stakeholder preference model.

5.2.2 Stakeholder Preference Model

Every requirement should be related to some measure of effectiveness to establish its level of achievement. In the case of a subjective requirement, the measure of effectiveness can also be qualitative. Since this requirement refers to the perceived look of the vehicle by the American population, it is important to create a preference model based on the both operational and systems alternatives. The survey created for this experiment can be found in Appendix C.

The first step in the creation of the survey was to define the shape, aesthetics and protocol into systems and operations. This definition process is illustrated in Figure 5.4. It represents a TOP-DOWN hierarchy, starting with the general components on the left (TOP), going into the systems and operations in the middle, and finishing with the systems and operational alternatives on the right (DOWN).

As it can be observed, the helicopter shape is divided into the cockpit and tail systems. The cockpit shape varies based on the nose length while the tail shape includes two discrete options, a fenestron (T1) and a more common external tail rotor tail (T2). The aesthetics is divided into the colors, paint schemes and sticker options. The operational characteristic of the requirement is defined with two protocols occurring during the departure and arrival ceremonies of the President. One protocol consists of having guards beside the helicopter's door, and the other protocol involves laying a red carpet as the dignitaries enter and exit the helicopter.

The survey uses two techniques to collect the participant preferences. The first technique uses pairwise comparison to evaluate which alternative is preferred, and the second technique asks the participant to rank which system makes the vehicle to look more presidential. Figure 5.5 shows an example of the two different types of questions asked to the participant.

The use of pairwise comparisons is meant to mimic the AHP pairwise comparison. As discussed earlier in this thesis, comparing alternatives in pair is an effective approach to structure the participant thinking process. Consequently, the pairwise comparison concept was extended to the survey in order to learn more about the advantages and disadvantages of comparing alternatives side by side.

The results of the survey are compiled differently for the ranking and pairwise comparison questions. Assuming N participants, the frequency of the pairwise comparison results are compiled in a matrix format. The process to obtain the ranking and normalized weighting of the alternatives is illustrated in Figure 5.6. In this process, it is important to note that the total number of comparisons vary depending on how many participants thought that the system or protocol had an impact on the requirement.

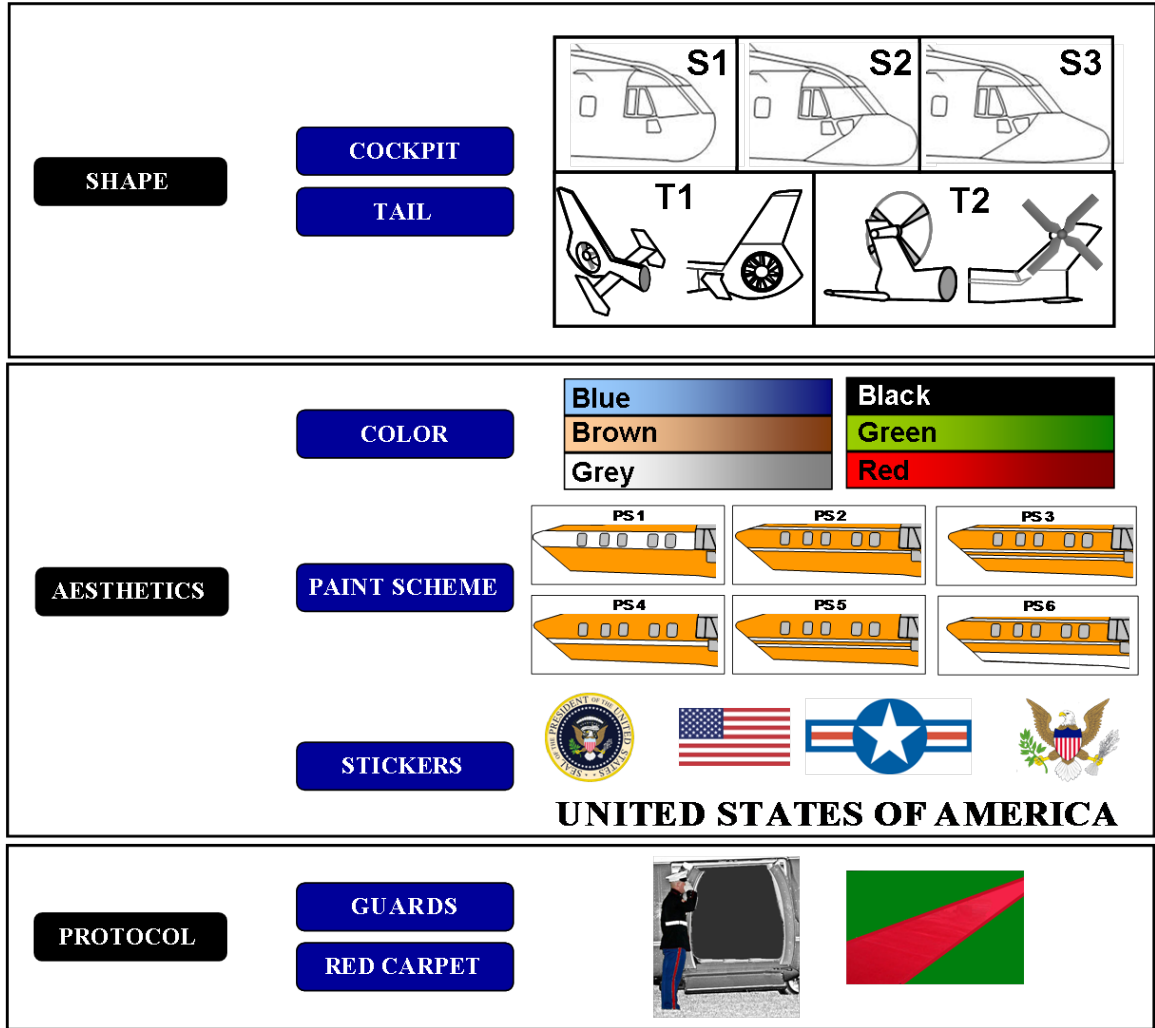
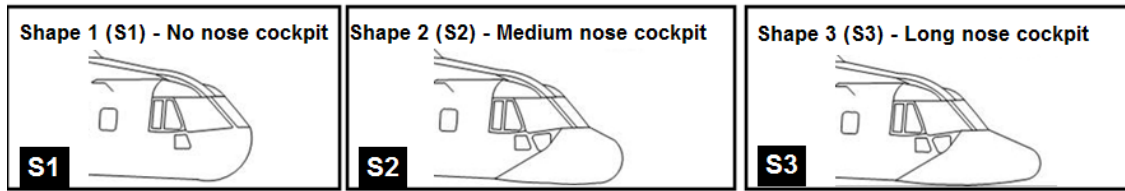


Figure 5.4: Requirement definition hierarchy.

The results from the ranking questions are calculated with a normalized weighted average. The scale used for the ranking results is depicted in Table 5.2. The normalized weighted average approach was selected for the ranking question because the participants are allowed to add systems and operational alternatives. The unpredictability of the new alternatives makes it difficult to use the pairwise comparison approach. Using a different technique to evaluate the weight is also beneficial to explore the differences between the pairwise comparison and the weighted average approaches. Also, note that the addition of new alternatives may sometimes result in a total normalized weighted average of less than one.



QUESTION 1 - COCKPIT:

Do you think that the cockpit nose shape has an impact on the "presidentiality" attribute of the vehicle?

YES NO

If YES, please circle your preference:

Concept _____ looks more "presidential" than Concept _____

- a) S1 OR S2
b) S1 OR S3
c) S2 OR S3

QUESTION 4 - RANK SHAPES:

Rank the different shapes, where (1) is the more presidential.

Please add the elements of QUESTION 3 to the ranking.

RANK	SHAPE
	Cockpit
	Tail

Figure 5.5: Example of stakeholder preferences survey questions.

Table 5.2: Ranking question weighting scale.

Rank	Scale Value
1	9
2	5
3	3
4	1

5.2.2.1 Results of the Survey

Ideally the American public population should be defined by a random sample representing the various age, ethnic and economic groups of the society. However, the objective of this experiment is to test the proposed methodology; consequently any sample of the population can be used to demonstrate how the information is used and managed in the creation of the stakeholder preference model. Consequently, this survey was given to 46 graduate students enrolled in the course AE 8804 Advanced Design Methods I.

The first result, illustrated in Figure 5.7, shows the percentage of the sample agreeing that the alternatives described in the survey have an impact on the presidential look of

1 – Comparison results of the survey are compiled in a matrix:

	S1	S2	S3
S1		$f_{1,2}$	$f_{1,3}$
S2	$f_{2,1}$		$f_{2,3}$
S3	$f_{3,1}$	$f_{3,2}$	

The frequency $f_{1,2}$ indicates the number of time that people preferred S1 over S2

2 – Sum each row:

$$Row_i = \sum_{j=1}^n f_{i,j}, \text{ for } i \neq j, n = \# \text{alternatives}$$

3 – Sum the total number of comparison (TC):

$$TC = \sum_{i=1}^n Row_i$$

4 – Normalize each row by TC

5 – Rank the alternatives

Cockpit Example						
	①	②	④	⑤		
	S1	S2	S3	Sum	(%)	Rank
S1		7	12	19	16.0	3
S2	33		26	59	49.6	1
S3	28	13		41	34.5	2
				119	100	
				③		

Figure 5.6: Compiling pairwise comparison preference.

the helicopter. It can be seen from this figure that the tail shape and paint scheme have the lowest impact (85%) on the helicopter appearance. The most influential elements are the colors and the stickers both with 100% of the population agreeing they impact the presidential appearance. Based on these results all the system and protocol alternatives were pursued for further analysis on their impact on the subjective requirement.

Figure 5.8 shows a summary of the results from questions 1, 2, 5, 6, 7 and 13. These results were obtained using both the weighted average and pairwise comparison techniques. The hierarchical top-Down format of Figure 5.8 starts with the most general concepts (*left*) going to the alternatives (*right*).

From the top-level (left) criteria, it can be seen that 43% of the participants judged that the aesthetics has the biggest impact on the presidential appearance of the helicopter, followed by the protocol (30%) and the shape (27%). The next level of the hierarchy presents the results of the sub-systems and operations. In aesthetics, the color has the biggest impact (44%), followed by the stickers (34%) and paint scheme (21%). The two predominant

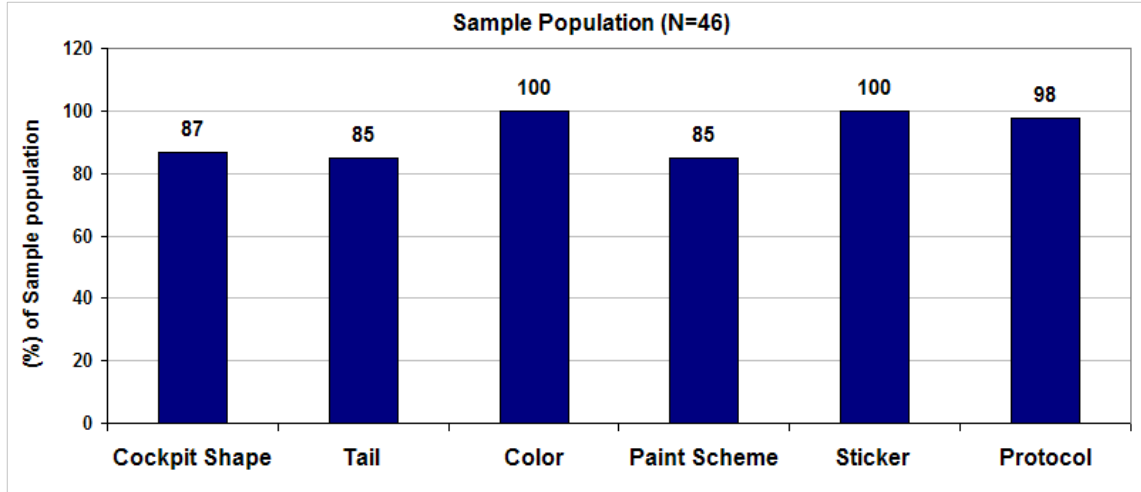


Figure 5.7: Element impacting the requirement.

colors are blue and black with 28% and 23% of the respondents respectively. The most important sticker to consider on the vehicle is the Presidential seal with 38%. Regarding the different paint schemes, it can be seen that none of the suggested designs stands out as more presidential. However, 85% of the respondents think that the paint schemes may influence the presidential appearance of the helicopter. This results suggests that either new paint schemes should be explored or to enlarge the pool of the sample population.

For the protocol, having guards standing by the helicopter during the departure and arrival ceremonies is judged to have a strong impact (59%) on the presidential appearance of the vehicle. The red carpet has a smaller influence (36%), but it can still be added without inferring too much cost to the overall system. Also when the participants were asked to select which one between the guards and the red carpet have the biggest impact on the presidential appearance of the vehicle, 93% of the respondents selected the guards in the pairwise comparison format. For the vehicle shape, the nose length of the cockpit was perceived to have a bigger impact (49%) on the presidential appearance than the tail (32%). Half of the respondents preferred the medium nose length over the other two designs. For the tail, the fenestron is largely preferred over the more common tail rotor by 77% of the participants

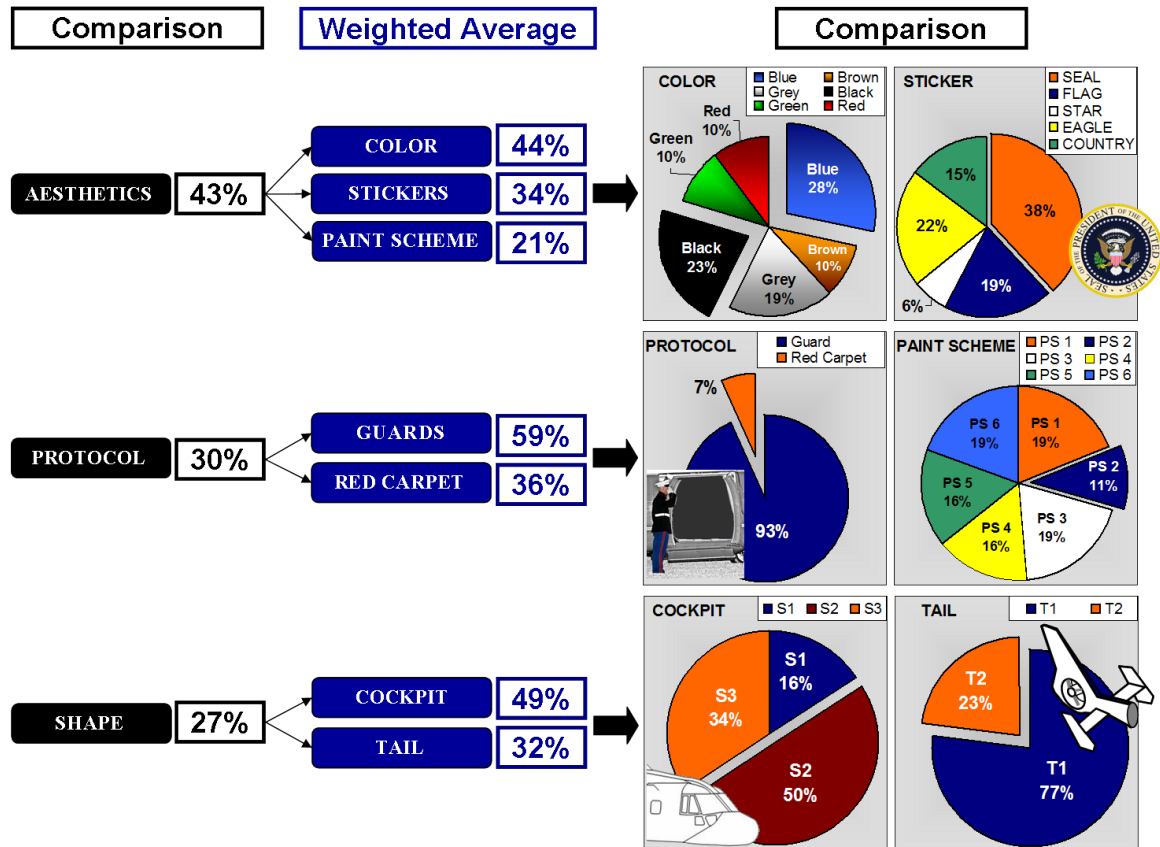


Figure 5.8: Results of the survey.

A clear distinction can be observed between the comparison and weighted average techniques. With the weighted average approach, the red carpet is ranked second by most of the respondents. A second position has a scale factor of 5 (Table 5.2), consequently when averaging over the entire sample of the population, even the second or a potential third alternative will represent a large influence on the requirement. With the pairwise comparison technique, the importance of the red carpet is reduced because most of the participants are preferring the guards; 93% guards and 7% red carpet. So which results should be considered and how should one solve this problem? For this experiment since the weighted average results are more balanced, they will be used to complete the preference model. However for the next experiment, one option to resolve this problem would be to compare the alternatives using a ratio scale to determine the strength of the preference. For instance, the participant should be able to input by how much an alternative is more important than another alternative. Note that this option is already embedded in the pairwise comparison performed in AHP.

Based on these results the next step is to create a decision model of the population preference with respect to the presidential appearance of the helicopter. This model can be used to verify if the final vehicle configuration satisfied the preferences of the population sample. Furthermore, the decision model can be enhanced by adding the impact of the alternatives on the vehicle's performance.

5.2.3 Creation of a Decision Model

The objective of the decision model is to combine the results of the survey in the hierarchical mapping. The notional hierarchy used to create the decision model is illustrated in Figure 5.9. This type of hierarchy can be used for many applications like strategic planning, alternative selection and resource allocation. For this experiment, the hierarchy is used to select the vehicle's shape with respect to performance, social and economics criteria. The decision makers can then select the alternatives by having a better understanding of the benefit and cost for each alternative. A series of steps is required to build such a decision model, and each of these steps provide additional knowledge regarding the requirement mapping, uncertainty analysis and requirements down-selection. The process is summarized as follows:

- A) Use the results from the survey to build the foundation of the decision model, and weighting of the alternatives;
- B) Define the mapping between the existing hierarchy and the performance, social and economic criteria;
- C) Perform a sensitivity analysis based on the importance the performance, social and economic benefit to identify a robust solution;
- D) Explore the impact of the weighting scenario on the selection of the alternatives.

Before going through these steps in detail, it is important to further describe the concepts presented in Figure 5.9. The hierarchy starts with a goal, and the achievement of this goal can be defined with criteria. The subsequent levels vary depending on the type of application. For this specific application, the lower levels of the hierarchy follow the requirements

taxonomy levels previously discussed in Figure 5.3. Consequently, the stakeholders and the systems are the next sub-levels of the hierarchy and the last level corresponds to the alternatives. Also note that the term *branch* is defined in this work as a single path taken between the initial goal and the systems alternatives. This term will be used in the discussion about the creation of a decision model.

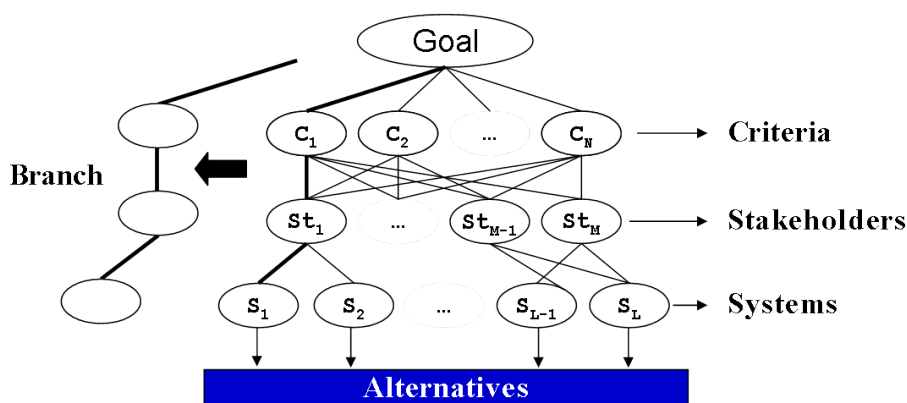


Figure 5.9: Decision model hierarchy.

A decision model can be created from a hierarchical structure by synthesizing the levels starting from the lowest level to the highest, bottom-up. Three techniques are explored to create a decision model from the results of the survey. The objective of these techniques is to determine the relative importance of the alternatives while taking into account the importance of the higher levels components. The first technique is a branch product approach; the second technique uses the conventional AHP synthesis from the SuperDecisions software [167], and the third technique explores a modified AHP synthesis approach.

The branch product approach multiplies the weight of every branch to determine the overall priority of the alternative. To illustrate this technique, the results of the survey are organized in a hierarchy as shown in Figure 5.10. In this figure, the category (left) represents the highest level and the alternatives the lowest level of the hierarchy. The results of the survey are used as weight for their respective component. Note that for the protocol results, only the weighted average values are used to create the decision model. The last column on the right represents the results of the branch product.

Category	System	Alternative		
SHAPE 0.27	COCKPIT 0.49	S1	0.16	0.02
		S2	0.50	0.07
		S3	0.34	0.05
	TAIL 0.32	T1	0.77	0.07
		T2	0.23	0.02
AESTHETICS 0.44	COLOR 0.44	BLUE	0.28	0.055
		BLACK	0.23	0.04
		GREY	0.19	0.04
		GREEN	0.10	0.02
		BROWN	0.10	0.02
		RED	0.10	0.02
	STICKERS 0.34	SEAL	0.38	0.06
		FLAG	0.19	0.03
		EAGLE	0.22	0.03
		COUNTRY	0.15	0.02
		STAR	0.06	0.01
	PAINT SCHEME 0.21	PS1	0.19	0.02
		PS2	0.11	0.01
		PS3	0.19	0.02
		PS4	0.16	0.01
		PS5	0.16	0.02
		PS6	0.19	0.02
PROTOCOL 0.30	GUARDS RED CARPET		0.59	0.18
			0.35	0.10

Overall Priority

Figure 5.10: Simple branch product decision model.

The priority results of the branch product approach are shown in Figure 5.11. The results indicate that the protocol alternatives are the most important to determine the presidential appearance of the helicopter. By comparing these results with the survey, one may argue that it does not match the preferences of the sample population. These results are skewed toward the protocol alternatives since the protocol category accounts for 30% of the presidential appearance, and this weight is divided between only two alternatives; whereas in the aesthetics category the total weight of 44% is divided into seventeen alternatives. Consequently, the branch approach results are strongly influenced by the number of alternatives which skewed the preference model toward the section of the hierarchy with the lowest number of alternatives. Therefore, there is a need to normalize the weighting so that it becomes independent of the number of alternatives, which leads to the second technique.

The second approach explored is the conventional AHP decision model built from the SuperDecisions software as illustrated in Figure 5.12. This figure shows the different clusters created to analyze the priority of the presidential helicopter alternatives. The results from the survey can be entered manually in the software as shown in Figure 5.13. SuperDecisions organizes all the alternatives and systems results in a matrix format. The steps to synthesize

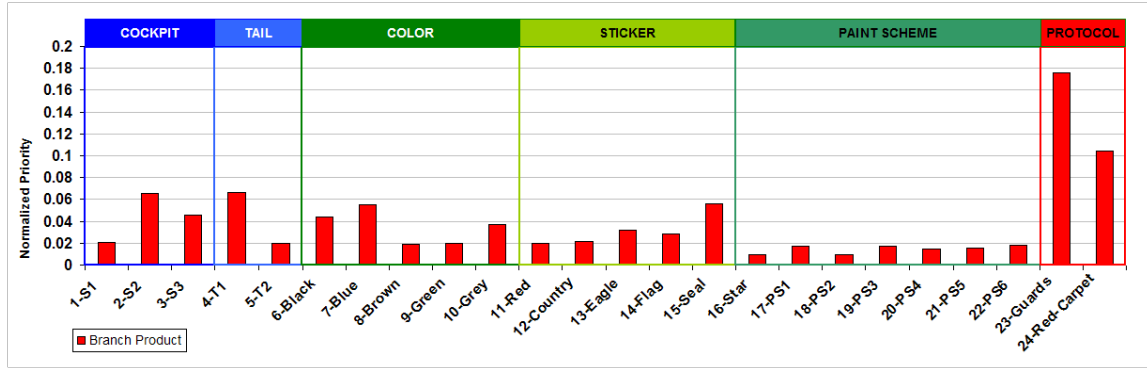


Figure 5.11: Priority from branch product model.

the importance of the alternatives in the hierarchy start by taking the limit of the results matrix as its power tends toward infinity; this result is called the limit matrix [157]. This limit matrix synthesized all the comparisons defined in the given hierarchy or network, including inter-dependencies between nodes. More detail about the mathematical foundation of the limit matrix can be found in section 3.3.4.

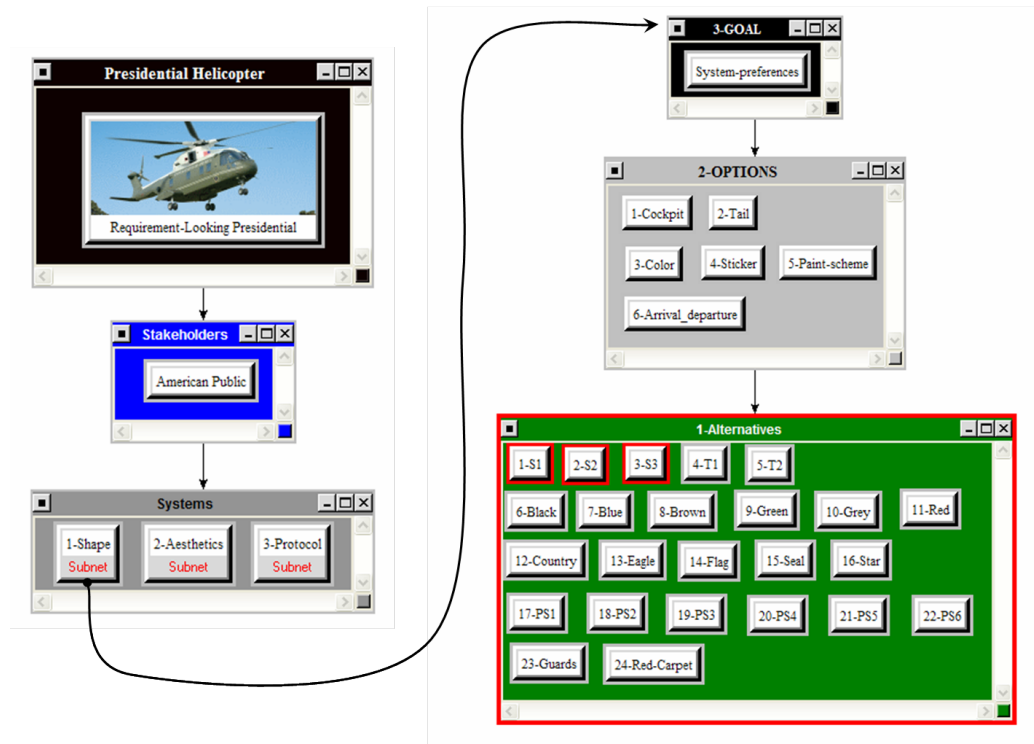


Figure 5.12: AHP decision model in SuperDecisions.

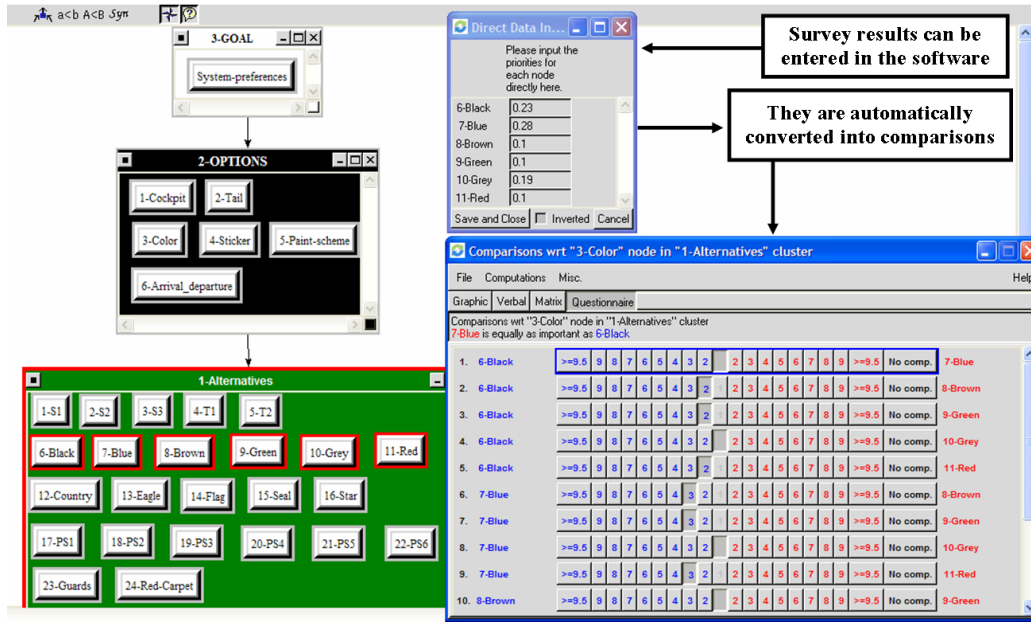


Figure 5.13: Survey results entered in SuperDecisions.

The alternative priorities obtained from SuperDecisions are compared with the branch approach in Figure 5.14. It can be observed that the results from SuperDecisions do not include the peaks of importance previously obtained from the branch product technique. The values are more evenly distributed following the relative importance of the vehicle shape, aesthetics and protocol. The most important vehicle characteristics are (starting with the most important) sticker, color, protocol, cockpit shape, tail shape and paint scheme.

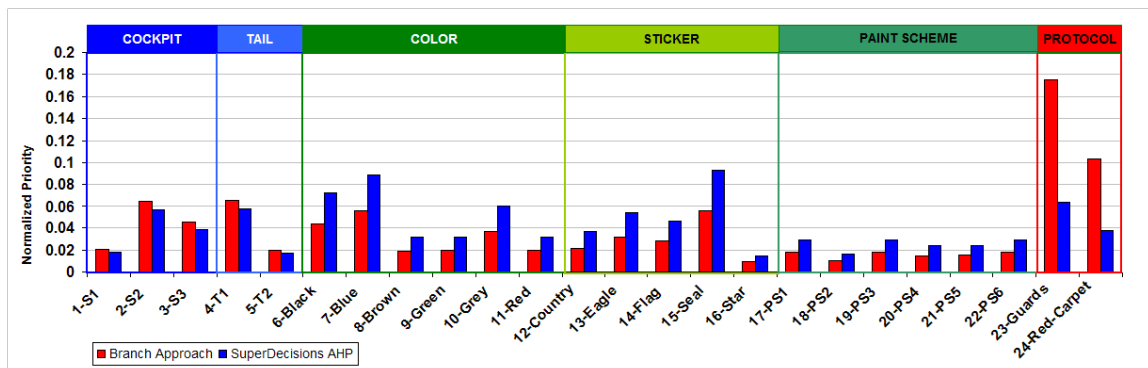


Figure 5.14: Priority comparison with AHP model.

One limitation of SuperDecisions is that all the alternatives must be located in one cluster. Consequently when the level of the hierarchy are synthesized, the software normalized

the priority based on the biggest values regardless of its cluster. To eliminate this limitation, a modified technique has been created to be able to synthesize the hierarchical levels following their pre-defined clusters.

The third technique is a modified version of the synthesis technique used in SuperDecisions. It starts by either using the results from the survey or the results of the limit matrix in SuperDecisions. This technique allows for the synthesis of multiple clusters of alternatives by using two types of normalization: Infinity and L1 norms. These norms are described mathematically as follows (Eq. 4.1).

$$\begin{aligned}
 \text{Given :} \quad & \vec{x} = [x_1, x_2, \dots, x_n] \\
 \text{Infinity norm :} \quad & \|\vec{x}\|_{\infty} = \max_i |x_i| \quad i = 1, \dots, n \\
 \text{L1 norm :} \quad & \|\vec{x}\|_1 = \sum_{i=1}^n |x_i| \quad i = 1, \dots, n
 \end{aligned}$$

The Infinity norm uses the highest magnitude of a given alternative clusters to normalize the other values of this cluster. The L1-norm is used to synthesize an entire level of the hierarchy by normalizing each priority by the sum of the priority of the level.

The process used to synthesize the hierarchical model is illustrated in Figure 5.15. The yellow lines define the various clusters. A level is synthesized by first using the Infinity norm to normalize the different clusters of the hierarchy, and then by multiplying the results of this normalization with the weight of the higher level element. For instance in Figure 5.15 the cockpit alternatives S1, S2 and S3 represent a cluster linked to the system *cockpit*. The cockpit alternatives values are normalized using the Infinity norm with the alternative S2 (step 1). Subsequently, the alternative values are multiplied with the importance of the cockpit value (step 2). The same process is repeated until all the clusters and levels are synthesized following the bottom-up process (steps 3 & 4). Finally at the last level of the hierarchy, all the priorities are normalized by using the L1 norm (step 5). Consequently, the sum of all priorities is equal to one, which makes it easier to determine the relative importance of the alternatives.

By using this approach, the priority of the alternative is not affected by the number of alternatives in the cluster, as is the case for the branch product model. The priority resulting

					①	②	③	④	⑤	
					INF-N	Synt. 1	INF-N	Synt. 2	L1-N	
SHAPE	0.27	COCKPIT	0.49	S1	0.16	0.32	0.158	0.322	0.086	0.018
				S2	0.50	1.00	0.490	1.000	0.267	0.056
				S3	0.34	0.69	0.341	0.695	0.185	0.039
		TAIL	0.32	T1	0.77	1.00	0.320	0.653	0.174	0.037
				T2	0.23	0.30	0.096	0.196	0.052	0.011
AESTHETICS	0.44	COLOR	0.44	BLUE	0.28	1.000	0.444	1.000	0.437	0.092
				BLACK	0.23	0.796	0.353	0.796	0.348	0.074
				GREY	0.19	0.673	0.299	0.673	0.294	0.062
				GREEN	0.10	0.352	0.156	0.352	0.154	0.033
				BROWN	0.10	0.337	0.149	0.337	0.147	0.031
				RED	0.10	0.357	0.158	0.357	0.156	0.033
		STICKERS	0.34	SEAL	0.38	1.000	0.335	0.755	0.330	0.070
				FLAG	0.19	0.511	0.171	0.386	0.169	0.036
				EAGLE	0.22	0.569	0.191	0.430	0.188	0.040
				COUNTRY	0.15	0.385	0.129	0.291	0.127	0.027
				STAR	0.06	0.167	0.056	0.126	0.055	0.012
		PAINT SCHEME	0.21	PS1	0.19	0.982	0.209	0.472	0.206	0.044
				PS2	0.11	0.549	0.117	0.263	0.115	0.024
				PS3	0.19	0.982	0.209	0.472	0.206	0.044
				PS4	0.16	0.814	0.173	0.391	0.171	0.036
				PS5	0.16	0.850	0.181	0.408	0.178	0.038
				PS6	0.19	1.000	0.213	0.480	0.210	0.044
PROTOCOL	0.30									
		GUARDS			0.59	1.00	1.000	1.000	0.296	0.063
		RED CARPET			0.35	0.59	0.593	0.593	0.176	0.037
					Sum					4.728
Represent a level or sub-level of the hierarchy										

Figure 5.15: Modified AHP model.

from the modified AHP approach are compared with the branch product and SuperDecisions approaches in Figure 5.16.

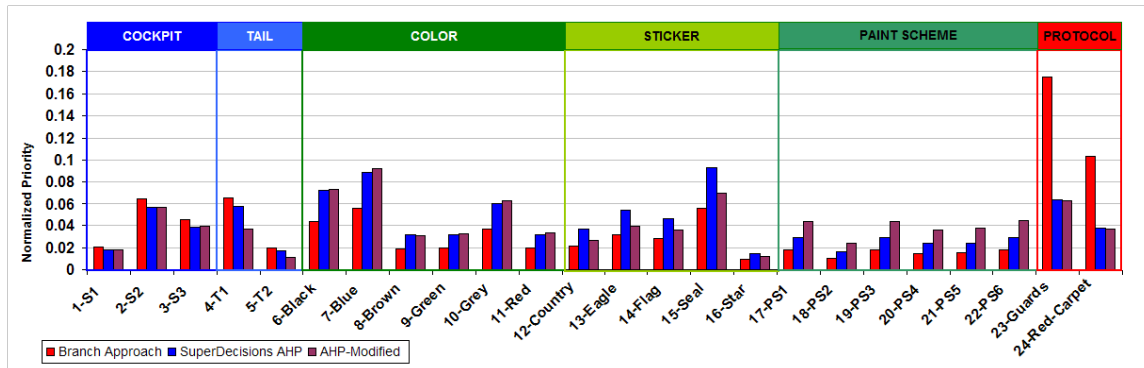


Figure 5.16: Priority results branch and modified AHP models.

By comparing the modified and SuperDecisions AHP results, one can observe that the modified approach reduce the tail and sticker priorities, and increase the color and paint scheme priorities. The cockpit and protocol results remain practically unchanged. These differences in priorities are caused by using different synthesis processes since both approaches utilized the results from the survey.

This section compared three techniques to synthesize the results of the survey into a decision model. The branch method was limited because it depends on the number of alternatives per cluster. The SuperDecisions software enables the creation of hierarchies or networks to determine the priority of alternatives, however it is limited to one alternative cluster during the synthesis process. Consequently the modified approach was created to take advantage of the SuperDecisions features while extending the synthesis process to account for multiple clusters of alternatives. The modified approach will be used for the down-selection of the alternatives based on a benefits and costs analysis discussed in the next section.

5.2.3.1 Benefits and Costs Model

The synthesis of the American public priorities in the previous section is useful to determine how well a given vehicle configuration satisfies the requirement “looking presidential”. However, for the design of the presidential helicopter, one can assume that this requirement is far less important than the operational and design requirements of the vehicle. Therefore how can decision makers evaluate the importance of this requirement in the overall down-selection of the alternatives? For this problem, other criteria like performance and economics aspects of the vehicle need to be taken into account. These criteria can be integrated into the hierarchical model in order to perform a benefits and costs analysis of the alternatives down-selection, as illustrated in Figure 5.17.

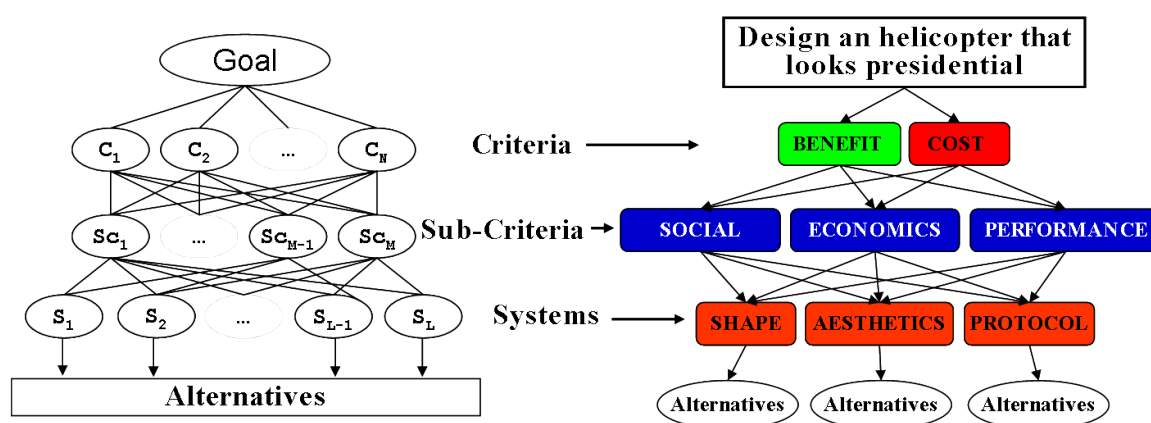


Figure 5.17: Decision model for Presidential appearance.

The benefits and costs decision model is frequently used with AHP and ANP [156, 155].

It provides enough flexibility to allow the use of stakeholder models with the addition of clusters to define other criteria. In this section, only the shape selection is analyzed in term of social, economics and performance criteria. The aesthetics and protocol dimensions have been ignored because they can be easily modified during the vehicle life cycle. On the other hand, once the shape alternatives are fixed in conceptual design, it becomes extremely difficult and costly to modify the design.

Figure 5.17 shows a level of sub-criteria that define the decision making process. The choice of sub-criteria is systems dependent. For the selection of the cockpit and tail alternatives, Figure 5.18 illustrates the attributes taken into account with respect to the performance, economics and social criteria of the vehicle, and how these attributes impact the different shape alternatives.

$$(Benefit / Cost)_{Performance} = f(\Delta Drag, \Delta Weight)$$

$$(Benefit / Cost)_{Economics} = f(Stakeholders, Resources, Reliability)$$

$$(Benefit / Cost)_{Social} = f(Stakeholders, Public Image, Safety)$$

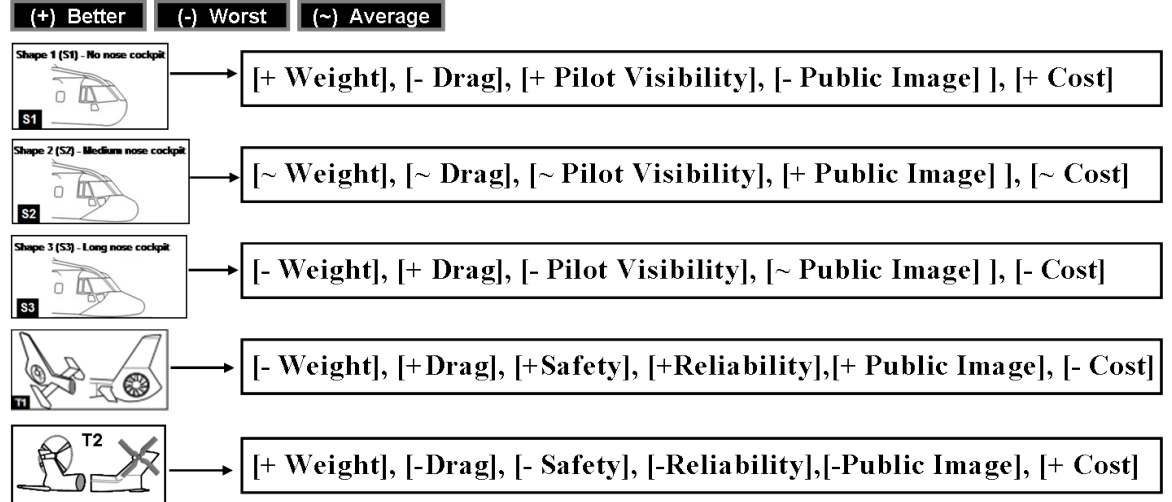


Figure 5.18: Benefits and costs of the shape selection.

The performance criterion of the alternatives is defined by the variation in weight and drag. The economic criterion takes into account the importance of the stakeholders, the available resources and the reliability of the various components. Finally the social criterion includes the importance of the stakeholders, the public image (presidential appearance), and

the safety characteristics of the alternatives.

This decision model can be made as complex as the stakeholders desire. Some of these attributes can be further decomposed, for instance the resources may be divided into recurring and non-recurring costs. This is the case of the Fenestron (tail-T1), since this technology is assumed to require additional research and development time for its integration to the vehicle. Furthermore, the cockpit safety attribute refers to the “pilot visibility”, assuming that better visibility reduces the risk of accidents during takeoff and landing. Ideally the stakeholders should be involved in the definition of the attributes and their impact on the system and operations. However, for this experiment, the main objective is to acquire more knowledge about the proposed methodology; consequently no external stakeholders were involved in the definition of these attributes.

The benefits and costs model is created using SuperDecisions to establish the clusters and the connections between the various components. The synthesis of the decision model is done using the modified AHP approach in Excel^(R). This approach provides more flexibility to perform and store the sensitivity analysis applied to the criterion’s weight. An example of the economics benefits model is shown in Figure 5.19. The highest level of the hierarchy corresponds to the goal of selecting the best shape alternatives as a function of the benefits and costs criteria. It is important to differentiate between the benefits and costs at the first level of the hierarchy, since all the subsequent pairwise comparisons are performed in terms of highest **benefits** or highest **costs**.

For example, when comparing both tail alternatives in term of “*Benefits-Economics-RDTE*”, tail T2 should have a greater importance than tail T1, because it is commonly implemented on the majority of helicopters. When comparing the same tail alternatives in terms of “*Costs-Economics-RDTE*”, tail T1 should be given a greater importance because it requires more time and money to integrate this alternative to the vehicle, therefore the cost should be higher. Differentiating between benefits and costs early in the decision process offers some additional flexibility to the decision makers, since the relationships between the benefits and costs are not necessarily proportional. The next step is to perform the pairwise comparisons based on the hierarchical decomposition of the problem.

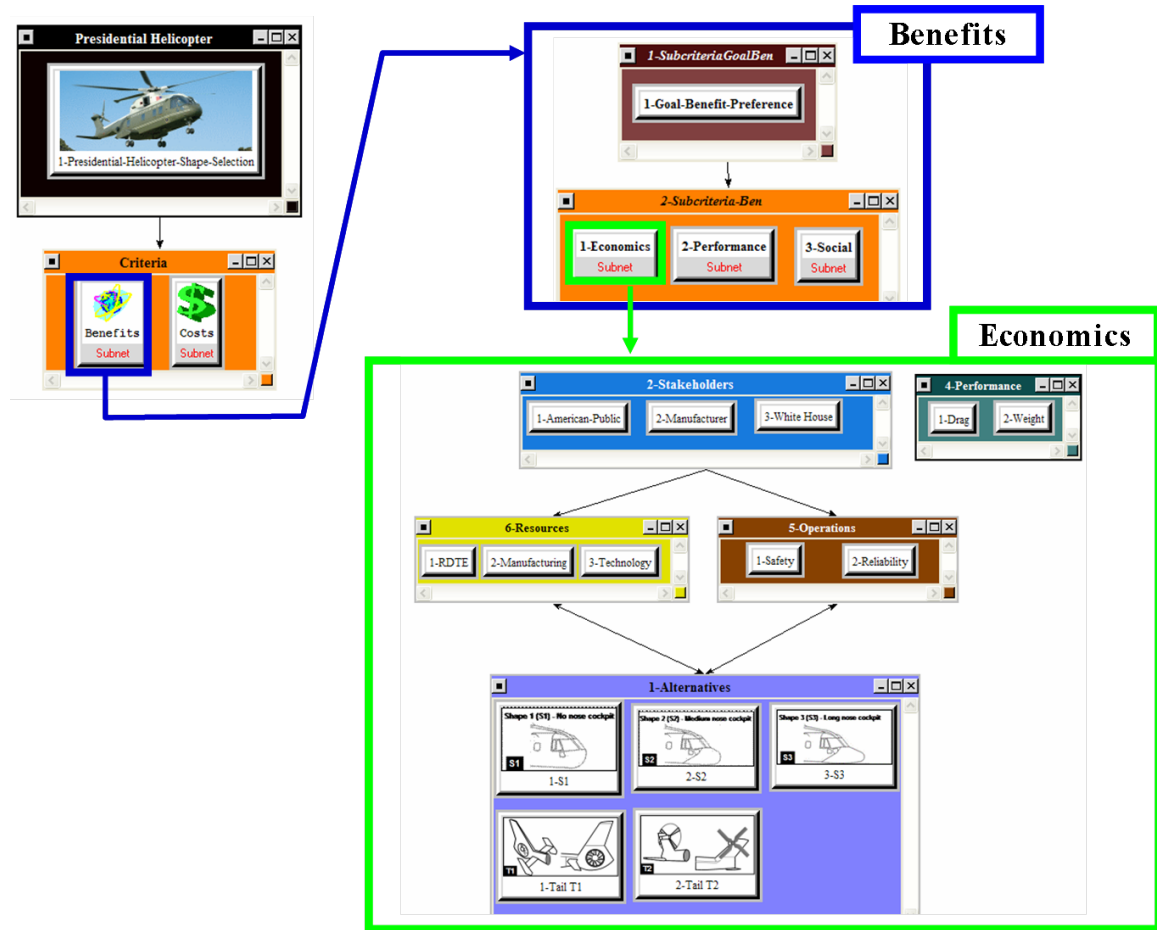


Figure 5.19: Benefits and costs decision model - Economic cluster in SuperDecisions.

The design team can structure the hierarchy or network by creating and linking as many elements as desired. Based on the initial relationships between the elements, a set of pairwise comparisons is created for the experts. SuperDecisions stores the results of the comparison in a matrix, as illustrated in Figure 5.20.

The columns and rows of the matrix correspond to the elements present in the “*Benefits-Economics*” hierarchy. The matrix is structured assuming that the row elements are compared with respect to column elements. For example, in Figure 5.20 the RDT & E and manufacturing costs are compared with respect to the cockpit S1. For this specific case, the manufacturing costs is assumed to be more important, because cockpit S1 is smaller implying less material and manufacturing time. Also, one can notice that the summation of every column is equal to one. This is done automatically by taking into account the results

		With respect to:														
BENEFITS	(weighted matrix)	1-S1	1-T1	2-S2	2-Tail	3-S3	1-AP	2-MaR	3-WH	1-Dr	2-Wt	1-Sa	2-Re	1-RD	2-MaC	3-TeK
ECONOMICS																
	1-S1	0	0	0	0	0	0	0	0	0	0	0	0	0.315	0.268	0
	1-Tail T1	0	0	0	0	0	0	0	0	0	0	0	0.667	0.082	0.090	0.25
	2-S2	0	0	0	0	0	0	0	0	0	0	0	0.000	0.245	0.171	0
	2-Tail T2	0	0	0	0	0	0	0	0	0	0	0	0.333	0.238	0.376	0.75
	3-S3	0	0	0	0	0	0	0	0	0	0	0	0	0.120	0.096	0
	1-American Public (AP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Manufacturer (MaR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-White-House(WH)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1-Drag (Dr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Weight (Wt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1-Safety (Sa)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Reliability (Re)	0	0.333	0	0.333	0	0	0.3333	0	0	0	0	0	0	0	0
	1-RDT&E (RD)	0.333	0.333	0.667	0.333	0.667	0	0.139	0	0	0	0	0	0	0	0
	2-Manufacturing Cost	0.667	0.333	0.333	0.333	0.333	0	0.441	0	0	0	0	0	0	0	0
	3-Technnology Cost	0	0	0	0	0	0	0.087	0	0	0	0	0	0	0	0
Comparison																

Figure 5.20: Results of comparisons from the economic benefits model.

from the clusters and nodes comparisons.

The matrix representing the performance and social benefits models are depicted in figures 5.21 and 5.22 respectively.

		1-S1	1-T1	2-S2	2-Tail	3-S3	1-AP	2-MaR	3-WH	1-Dr	2-Wt	1-Sa	2-Re	1-RD	2-MaC	3-TeK
BENEFITS																
PERFORMANCE																
	1-S1	0	0	0	0	0	0	0	0	0.068	0.238	0	0	0	0	0
	1-Tail	0	0	0	0	0	0	0	0	0.229	0.075	0	0	0	0	0
	2-S2	0	0	0	0	0	0	0	0	0.128	0.134	0	0	0	0	0
	2-Tail	0	0	0	0	0	0	0	0	0.068	0.221	0	0	0	0	0
	3-S3	0	0	0	0	0	0	0	0	0.256	0.082	0	0	0	0	0
	1-American Public (AP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Manufacturer (MaR)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	3-White-House(WH)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1-Drag (Dr)	0.25	0.8	0.5	0.2	0.8	0	0.2	0	0	0	0	0	0	0	0.3333
	2-Weight (Wt)	0.75	0.2	0.5	0.8	0.2	0	0.8	0	0	0	0	0	0	0	0.6667
	1-Safety (Sa)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Reliability (Re)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1-RDT&E (RD)	0	0	0	0	0	0	0	0	0.167	0.135	0	0	0	0	0
	2-Manufacturing Cost	0	0	0	0	0	0	0	0	0.083	0.041	0	0	0	0	0
	3-Technnology Cost	0	0	0	0	0	0	0	0	0.000	0.074	0	0	0	0	0

Figure 5.21: Results of comparisons from the performance benefits model.

		1-S1	1-T1	2-S2	2-Tail	3-S3	1-AP	2-MaR	3-WH	1-Dr	2-Wt	1-Sa	2-Re	3-PI	1-RD	2-MaC	3-TeK
BENEFITS																	
SOCIAL																	
	1-S1	0	0	0	0	0	0	0	0	0	0	0.138	0	0.055	0	0	0
	1-Tail	0	0	0	0	0	0	0	0	0	0	0.246	0	0.184	0	0	0
	2-S2	0	0	0	0	0	0	0	0	0	0	0.138	0	0.258	0	0	0
	2-Tail	0	0	0	0	0	0	0	0	0	0	0.073	0	0.058	0	0	0
	3-S3	0	0	0	0	0	0	0	0	0	0	0.073	0	0.111	0	0	0
	1-American Public (AP)	0	0	0	0	0	0	0	0	0	0	0.167	0	0.167	0	0	0
	2-Manufacturer (MaR)	0	0	0	0	0	0	0	0.667	0	0	0	0	0	0	0	0
	3-White-House(WH)	0	0	0	0	0	0.667	0	0	0	0	0.167	0	0.167	0	0	0
	1-Drag (Dr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Weight (Wt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1-Safety (Sa)	0	1	0	1	0	0	0	0.333	0	0	0	0	0	0	0	0
	2-Reliability (Re)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-Public Image (PI)	0	0	0	0	0	0.333	0	0	0	0	0	0	0	0	0	0
	1-RDT&E (RD)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2-Manufacturing Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3-Technnology Cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.22: Results of comparisons from the social benefits model.

Looking at the results of figures 5.21 and 5.22 can provide a better understanding of the decision makers preferences, and the mapping between the elements. The next step synthesizes the pairwise comparison results by taking the limit of the matrix. In Reference

[156], Saaty discussed that the priorities matrix components can be defined according to their influence on each other. Consequently, by taking the limit of a matrix as its power tends toward infinity, one can determine the relative influence of all the elements of a matrix. The limit matrix of the economics benefits model is shown in Figure 5.23.

	1-S1	1-T1	2-S2	2-Tail	3-S3	1-AP	2-MaR	3-VH	1-Dr	2-Wt	1-Sa	2-Re	1-RD	2-MaC	3-TeK
1-S1	0.105	0.105	0.105	0.105	0.105	0	0	0	0	0	0	0.105	0.105	0.105	0.105
1-Tail T1	0.125	0.125	0.125	0.125	0.125	0	0	0	0	0	0	0.125	0.125	0.125	0.125
2-S2	0.075	0.075	0.075	0.075	0.075	0	0	0	0	0	0	0.075	0.075	0.075	0.075
2-Tail T2	0.157	0.157	0.157	0.157	0.157	0	0	0	0	0	0	0.157	0.157	0.157	0.157
3-S3	0.039	0.039	0.039	0.039	0.039	0	0	0	0	0	0	0.039	0.039	0.039	0.039
1-American Public (AP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-Manufacturer (MaR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-White-House(VH)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Drug (Dr)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-Weight (Wt)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1-Safety (Sa)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-Reliability (Re)	0.141	0.141	0.141	0.141	0.141	0	0.141	0	0	0	0	0.141	0.141	0.141	0.141
1-RDT&E (RD)	0.181	0.181	0.181	0.181	0.181	0	0.181	0	0	0	0	0.181	0.181	0.181	0.181
2-Manufacturing Cost	0.178	0.178	0.178	0.178	0.178	0	0.178	0	0	0	0	0.178	0.178	0.178	0.178
3-Technnology Cost	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0	0

Figure 5.23: Limit matrix of the economic benefits model.

From Figure 5.23, it can be seen that the results of a limit matrix give the same numerical value for each row. These values correspond to the relative importance of the elements included in the model. The decision makers can look at these values and perform a sanity check to evaluate the pertinence of the results. For instance, based on the comparison results, the reduction of the RDT&E is the resource having the greatest influence on the shape alternatives. Assuming that the decision makers are satisfied with the relative weighting of the model elements, the next step is to extract the relative importance of the shape alternatives.

The importance values are normalized separately for the cockpit and tail alternatives using the modified AHP approach. Figure 5.24 shows these normalized results as a function of the economics, performance and social criteria. A normalized importance of 1 corresponds to the best benefits that can be obtained in a specific criteria. At this point of the synthesis process, these normalized results do not include the decision maker's preferences regarding the importance of the economics, performance and social criteria. These preferences are synthesized at the end of the bottom-up process.

Before performing the synthesis of the whole model, the synthesis of the cost model also needs to be computed as a function of the economics, performance and social criteria. While

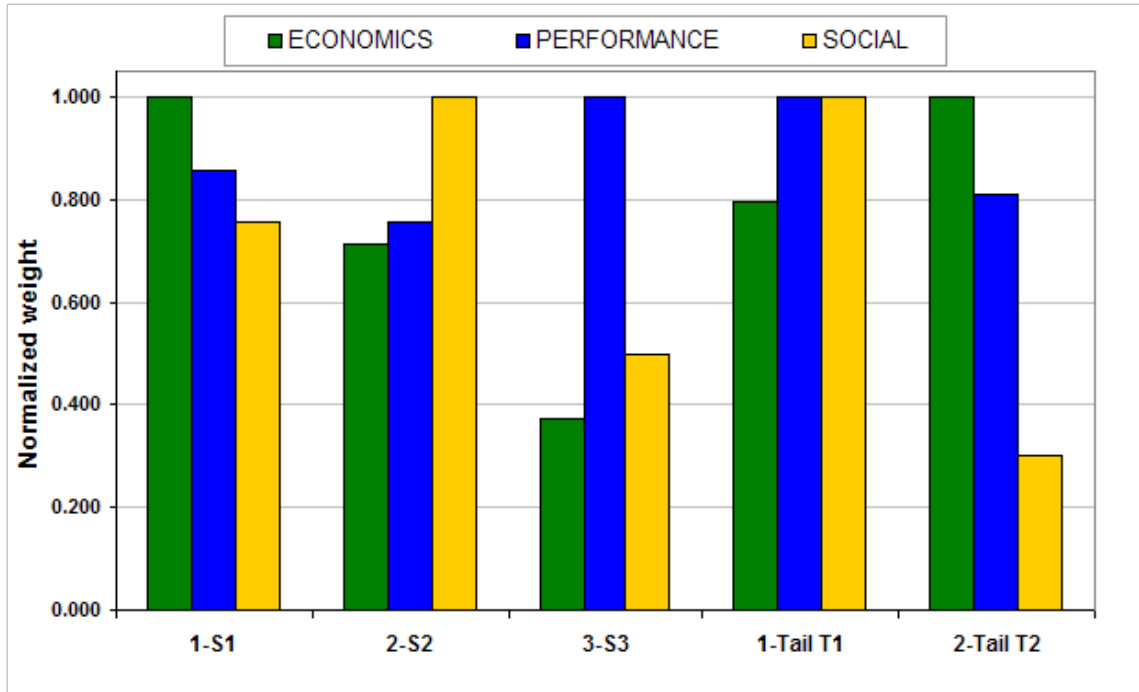


Figure 5.24: Synthesis of the economic, performance and social benefits.

creating the cost model, the decision makers need to pay special attention to compare the alternative by giving the highest weight to the alternative that they think is **more** costly. This may appear counter-intuitive to some, however when the final synthesis is performed the alternatives costs are subtracted from the benefits, and consequently the worst alternative needs to be the one that “cost” more. A different logic could be used, but it is important to make sure that the final synthesis of the model is consistent with the logic established at the beginning of the process. A new set of comparisons is performed for the costs model, and the normalized results are depicted in Figure 5.25.

It can be seen from Figure 5.25, that the cockpit S3 is judged to have the highest costs in terms of economics and social criteria, and the second highest cost in terms of performance. Consequently, regardless of the weight assigned to the criteria this cockpit (long nose) can be expected to have the lowest benefits to costs value. Regarding the tail alternative, the tail T1 has the highest costs in terms of the economics and performance criteria and the lowest cost value with respect to the social criteria. These values imply that tail T1 includes a new technology (worst economics), adds some weight to the vehicle (worst performance), but

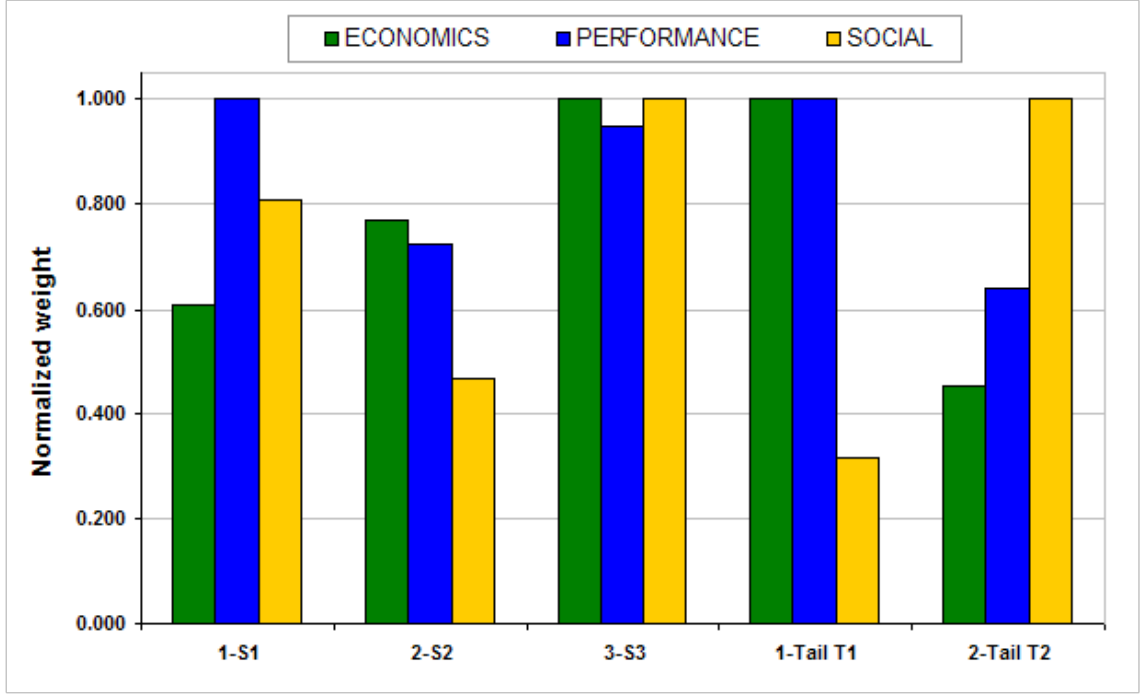


Figure 5.25: Synthesis of the economic, performance and social costs.

makes the overall vehicle safer and less likely to be involved in an accident (better social). Consequently, depending on the weights assigned to the respective criteria the choice of tail will fluctuate between the two alternatives.

The synthesis of the overall benefits and costs for the alternatives correspond to the last step of the hierarchy bottom-up process. In his books on decision making with the Analytic Network Process [157, 155], Saaty described the multiplicative and additive approaches to synthesize the benefits and costs. The multiplicative approach takes the ratio of the benefits over the costs as depicted in Equation 5.2, whereas the additive approach subtracts the costs from the benefits as depicted in Equation 5.3.

$$\frac{Benefits}{Costs} = \frac{W_E||B_{Economic}|| + W_P||B_{Performance}|| + W_S||B_{Social}||}{W_E||C_{Economic}|| + W_P||C_{Performance}|| + W_S||C_{Social}||} \quad (5.2)$$

$$Benefits - Costs = \frac{W_E||B_{Economic}|| + W_P||B_{Performance}|| + W_S||B_{Social}|| - [W_E||C_{Economic}|| + W_P||C_{Performance}|| + W_S||C_{Social}||]}{[W_E||C_{Economic}|| + W_P||C_{Performance}|| + W_S||C_{Social}||]} \quad (5.3)$$

These equations show how the importance of the criteria (W) are combined with the benefits and costs normalized values. An example of the final synthesis process is illustrated

in Figure 5.26, it starts with the results of the limiting matrix (1), which are normalized using the infinity norm (2). The next step uses the criteria weights to synthesize the weights of the shape alternatives (3). The L1-norm is then used to combined the results of the three criteria (4), and these values are used to calculate the final benefits per alternative. It can be observed that this synthesis process is the same as the one used for the presidential helicopter survey.

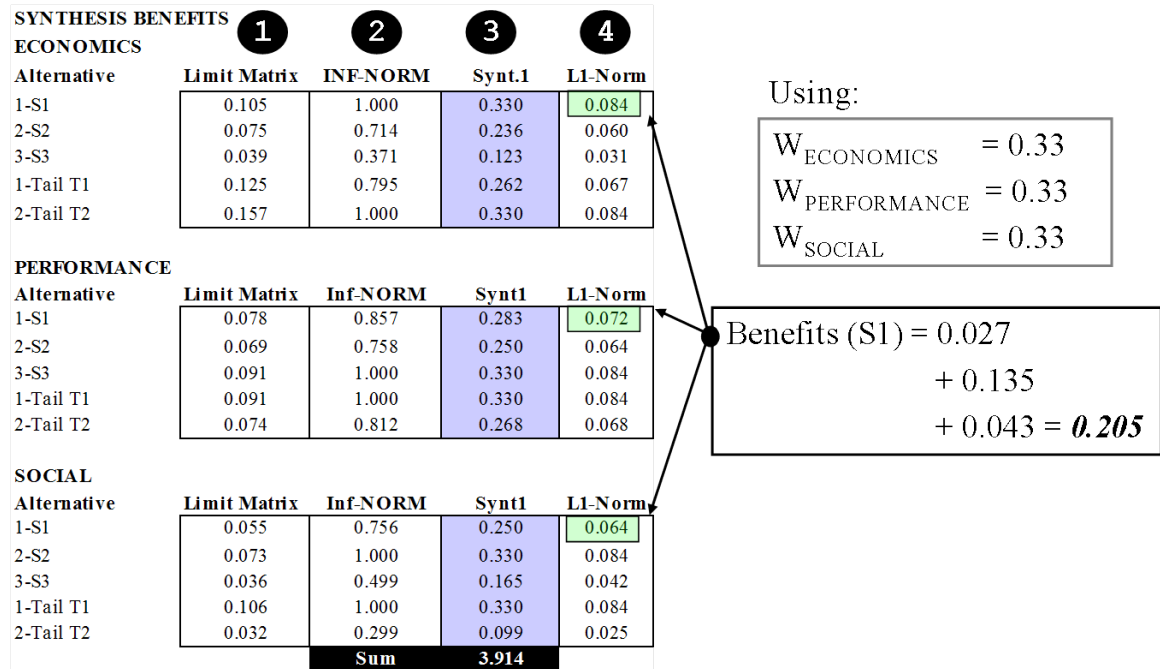


Figure 5.26: Synthesis of the alternative benefits.

In Figure 5.26 the additive approach is used to synthesize the alternatives. During this experimentation, both the multiplicative and additive approaches are tested to select the most appropriate technique for further analyses. Examples of using both approaches are shown in figures 5.27 and 5.28. These figures are created using an equal weighing of 0.33. The selection of the synthesis approach is based on two attributes: (1) the quality of the alternatives ranking, and (2) the information gathered from the results.

Regarding the quality of the alternative ranking, since both benefits and costs values are normalized to 1, both approaches give the same ranking of alternatives. In general, it is a difficult task to validate the ranking when the selection process includes tangible (i.e., costs) and intangible (i.e., public image) attributes. Wijnmalen performed a study on the benefits,

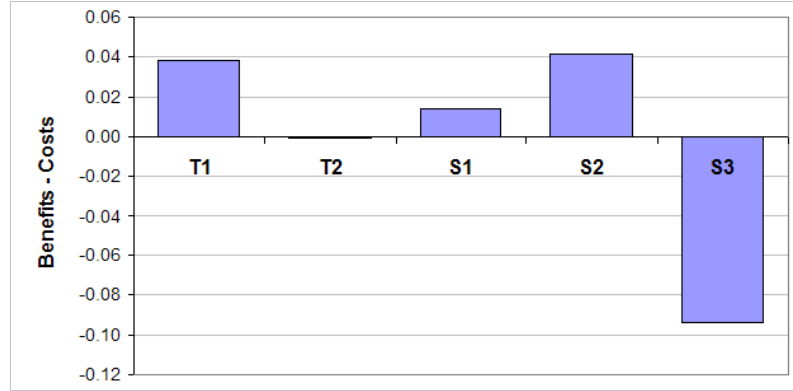


Figure 5.27: Example of synthesis using the additive approach.

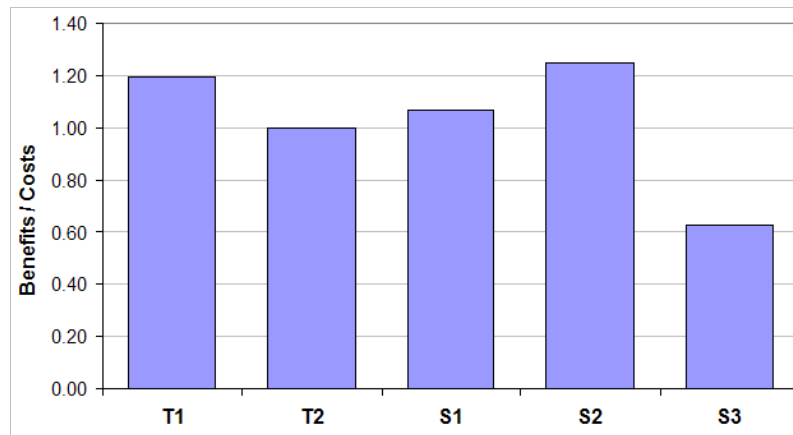


Figure 5.28: Example of synthesis using the multiplicative approach.

opportunities, costs and risks synthesis using AHP and ANP [193]. Based on the analysis of previous scenarios, he found that only the additive approach yields correct ranking of the alternatives and correct indication of profitability.

The information gathered from the results depends on how easy it is to differentiate the importance of the alternatives. Wijnmalen argues that the multiplicative approach produces non-intuitive results, whereas the additive approach is recommended for net value analysis [193]. For instance when the benefits and costs are equal, then there is no real benefit or cost of choosing an alternative, consequently and the intuitive results would be 0. Furthermore, Millet et al. argues of the importance of allowing negative preferences into AHP, which is achieved with the additive approach. By looking at figures 5.27 and 5.28, one can see that the additive approach provide a better representation of the net benefits or costs, and

that the multiplicative approach produces results that are not as intuitive. Therefore, the additive approach was selected to perform the uncertainty analysis and down-selection of alternatives.

5.2.3.2 Uncertainty Analysis and Down-Selection Based on the Hierarchical Decision Model

Two techniques are explored to analyze the impact of the criteria on the final selection of the alternatives, sensitivity analysis and the Monte-Carlo simulations (sections 3.4.1 & 3.4.2). The objective of these analyses is to determine how the ranking of alternatives is influenced by the importance of the criteria, which can be considered as epistemic uncertainty. A sub-objective is to determine if there is a robust selection of alternatives that satisfy more than one weighting scenario. The two approaches use different techniques to achieve these objectives. The sensitivity analysis linearly varies the importance of two criteria while keeping one criteria fixed, and based on these weights calculate the benefits and costs of alternatives. The Monte-Carlo technique is a stochastic process that applies distributions to the importance of the criteria, and based on these distributions performed a given number of simulations which randomly selected a value of the criterion's weight to evaluate the benefits and costs of alternatives. Both the sensitivity analysis and Monte-Carlo approaches are described in this section.

For the down-selection of the shape alternative, the sensitivity analysis is used to test the robustness of the alternative and to identify the critical elements of the decision. In this context the critical elements correspond to the importance of the criteria. The process used to achieve these results starts by creating an algorithm to allocate the importance value as illustrated in Figure 5.29. The process is iterative and increments the weights in order to calculate the benefits and costs of the alternatives. The sum of the weights is constrained to 1, consequently two values are needed to calculate the third weight. In this analysis the economic weight is chosen as the fixed value, but any of the two other criteria could have been used.

The results of the sensitivity analysis are shown in figures 5.30 and 5.31. An increment of 0.2 is used for the economic weight, and an increment of 0.1 is used for the social weight.

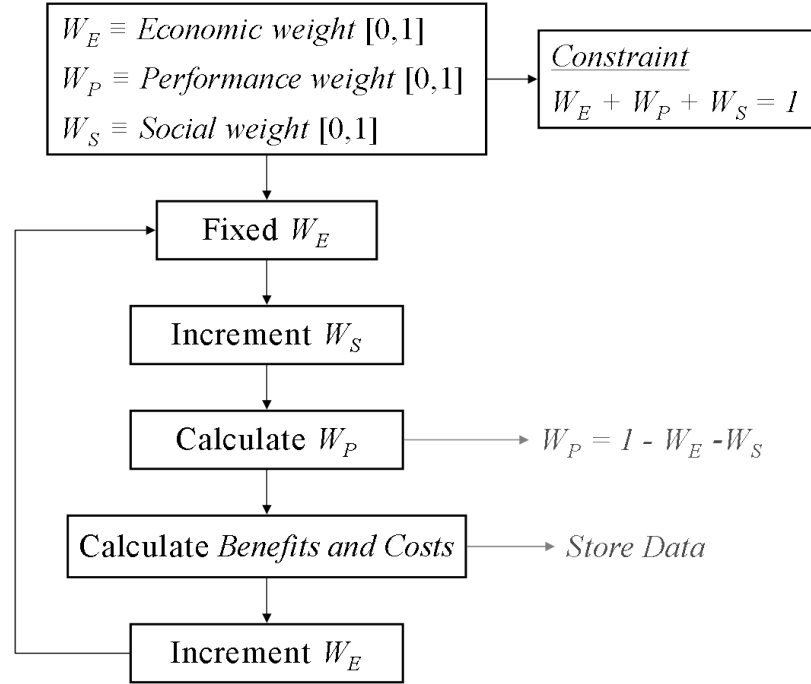


Figure 5.29: Sensitivity analysis logic.

The x-axis of the sensitivity plots includes both the social and performance importance, while the y-axis corresponds to the difference between the benefits and the costs of the alternative. It can be observed that the sum of the criterion weights (x-axis) respect the weighting constraint of one.

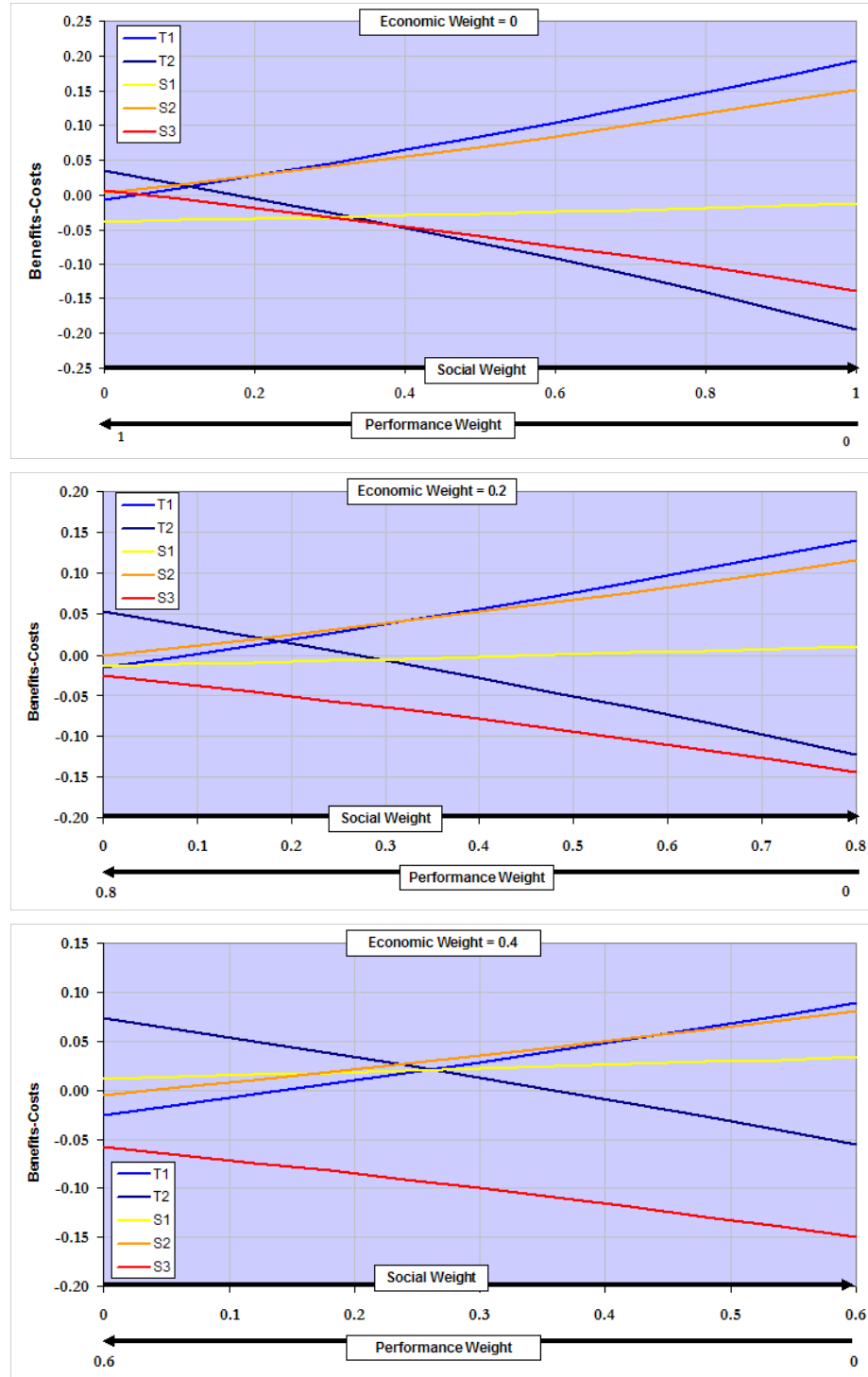


Figure 5.30: Sensitivity analysis of the criteria with economic weights of 0, 0.2 & 0.4.

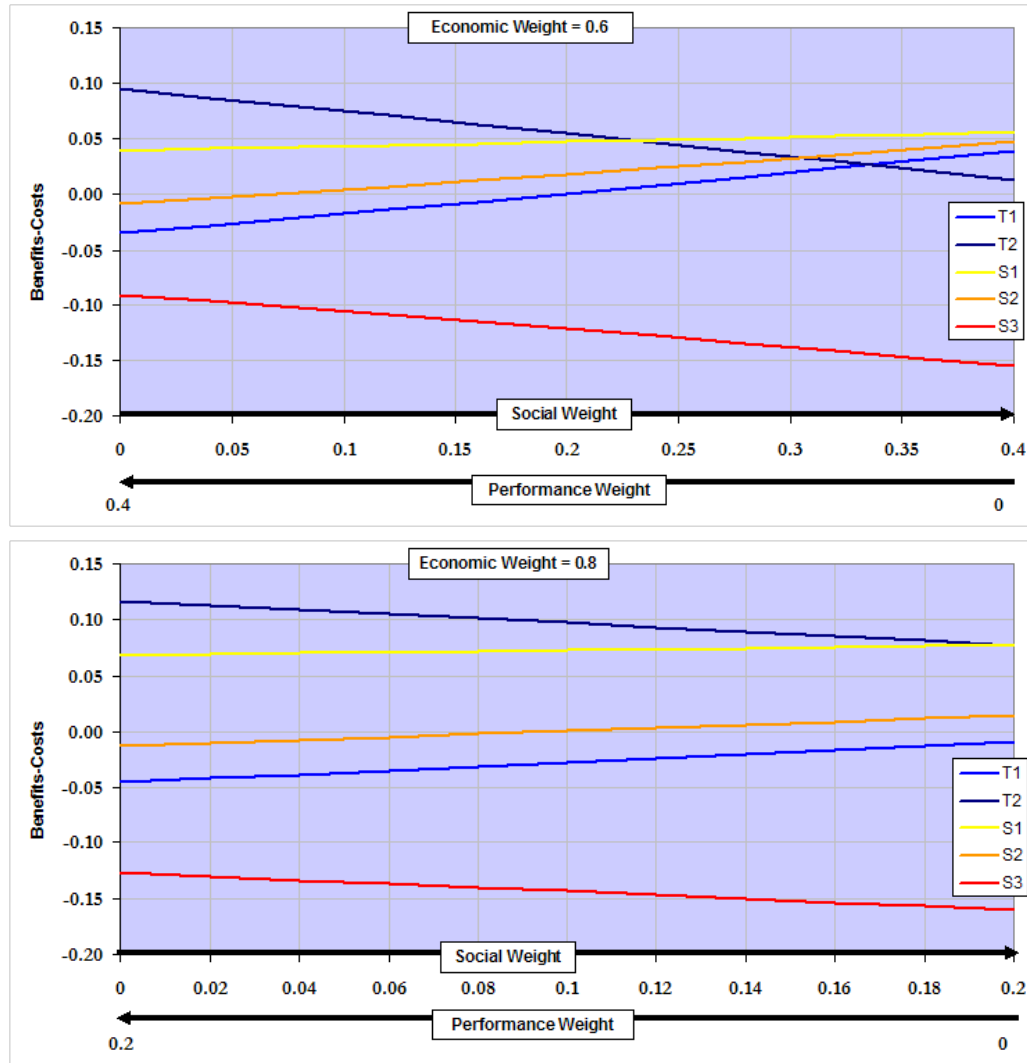


Figure 5.31: Sensitivity analysis of the criteria with economic weights of 0.6 & 0.8.

By looking at figures 5.30 and 5.31, it is desired (1) to find if there is a robust choice of alternatives, and (2) to gain critical knowledge from the analysis. Having the importance varying from one figure to the next makes it difficult to dissect the information in order to find a robust solution. To make this task easier, Table 5.3 has been created to depict the ranking of the alternatives as a function of the economic weight. For a given economic importance, when the ranking is changing due to the variation of the social and performance weighting, the dominant criteria making this alternative rank #1 is written next to it. The range in bracket next to the criteria represents the range of importance for which this

alternative dominates the other(s).

Table 5.3: Results from the criteria sensitivity analysis.

		Economic Weight				
	Ranking	0.0	0.2	0.4	0.6	0.8
TAIL	1	T1, S = [0.1,1]	T1, S = [0.19,0.8]	T1, S = [0.27,0.6]	T2, P = [0.06,0.4]	T2
	2	T2, P = [0.9,1]	T2, P = [0.61,0.8]	T2, P = [0.33,0.6]	T1, S = [0.34,0.4]	T1
COCKPIT	1	S2	S2	S2, S = [0.17,0.6]	S1	S1
	2	S1*	S1	S1, P = [0.43,0.6]	S2	S2
	3	S3*	S3	S3	S3	S3
<i>* Share the second rank</i> <i>S = Social weight</i> <i>P = Performance weight</i>						

From Table 5.3 one can notice that when the economic weight is lower than 0.6, tail T1 and cockpit S2 dominate the other alternatives. For the tail, if the stakeholders are inclined toward a high performance alternative, T2 dominates T1. For the cockpit, S2 dominates the other alternatives when the economic importance is smaller and equal to 0.2. For economic weights higher than 0.2 and smaller than 0.6, cockpit S2 is still dominant for a large range of social weighting. For economic weights higher than 0.6, it can be seen that tail T2 and cockpit S1 dominate the other options.

For the tail alternatives, the impact of having a new technology (tail T1) with a high economical preference makes tail T2 the dominant alternative. For the cockpit, using less material and manufacturing time (economic) makes the alternative S1 dominant over the other options. Consequently, no alternative selection is robust for all the possible weighting scenarios, however some alternatives are robust for a certain range of weight. The stakeholders can use this information to perform “what if” scenario or help the decision makers to reach a consensus on the alternative selection.

Other knowledge can also be extracted from this type of analysis. For instance, the economic weight has a great impact on the cockpit selection, since the ranking of the alternatives varies only so slightly as a function of the social and performance criteria. The same argument is not valid for the tail alternatives. Even though the economic criterion has some impact on the tail ranking, the social criterion also seems to be important. To validate this assertion, the same analysis has been performed while first fixing the performance weight and varying the economic and social importance. The results of this analysis can be seen in



Figure 5.32: Tail sensitivity analysis by fixing the performance criterion.

Figure 5.32.

It is interesting to notice that the slope of the curves T1 and T2 are not changing by increasing the weight of the performance criterion. The magnitude of the slope is also an indication of the impact of a criterion on the benefits and costs of the alternatives. Table 5.4 lists the slope magnitude of the benefits-costs curves while fixing one criterion.

Table 5.4: Benefits and Costs curve slopes.

Fixed Criterion	T1 Slope	T2 Slope	S1 Slope	S2 Slope	S3 Slope
Economic	0.2	-0.229	0.026	0.149	-0.145
Performance	-0.25	0.335	0.111	-0.169	-0.027
Social	-0.05	0.105	0.136	-0.020	-0.172

For the tail alternatives, it is observed that the slope is at its lowest magnitude when the social weight is fixed, which confirmed that the social criterion has the biggest impact on the benefits and costs value. This deduction is consistent with the results of the benefits and costs synthesis presented in figures 5.24 and 5.25.

For the cockpit alternatives, it is observed by looking at the slope magnitude that alternative S1 is strongly influenced by the economic criterion; alternative S2 is strongly influenced by the social criterion; and that the alternative S3 is strongly influenced by the performance

criterion. Therefore, the choice of cockpit alternatives can be expected to fluctuate more as the stakeholders are conducting “what if” scenarios.

Some drawbacks of sensitivity analysis occur as the number of criteria increases. The importance allocation algorithm becomes more complex, which makes it difficult to plot the results. Harder to understand plots imply a lower quality of knowledge extracted from the sensitivity analysis. A solution to that problem is to select the most important criteria, and then perform a more detailed sensitivity analysis. Another solution consists of using Monte-Carlo simulation on the criterion’s weight and evaluating the benefits and costs of alternatives for a large number of simulations. The objectives of using this technique are the same as for the sensitivity analysis: (1) find if there is a robust choice of alternative, and (2) to gain more knowledge from the decision model.

The Monte-Carlo process starts by applying a distribution on the desired input variables and determining the number of simulations. The simulation begins by using a random number from the pre-defined input distributions, and subsequently calculating the desired response(s). For this selection process, the input variables correspond to the importance of the criteria, and the response is the benefits and costs value. A uniform distribution is applied to the input variables, because it is desired to explore the full spectrum of the importance of the criteria. Since the weights of the criterion are dependent on each other, an algorithm was created to perform the weight assignment, as illustrated in Figure 5.33.

The objective of this algorithm is to obtain the same type of Probability Density Function (PDF) for the weight of the criteria. This ensures that the criteria are equally taken into account during for the Monte-Carlo simulations. The approach taken to achieve this result consists of using a counter variable that sequentially changes the criterion varying between 0 and 1. From Figure 5.33, once the first weight is known (X), the second weight uniform distribution is limited between 0 and $1-X$. After randomly selecting a value for the second weight (Y), the third weight is calculated based on the two other weights, $1-X-Y$. The benefits and costs value is then calculated for each alternative, and the counter variable is incremented to change the weighting assignment sequence. For this analysis, 10,000 Monte-Carlo simulations are performed and the results are stored in a database.

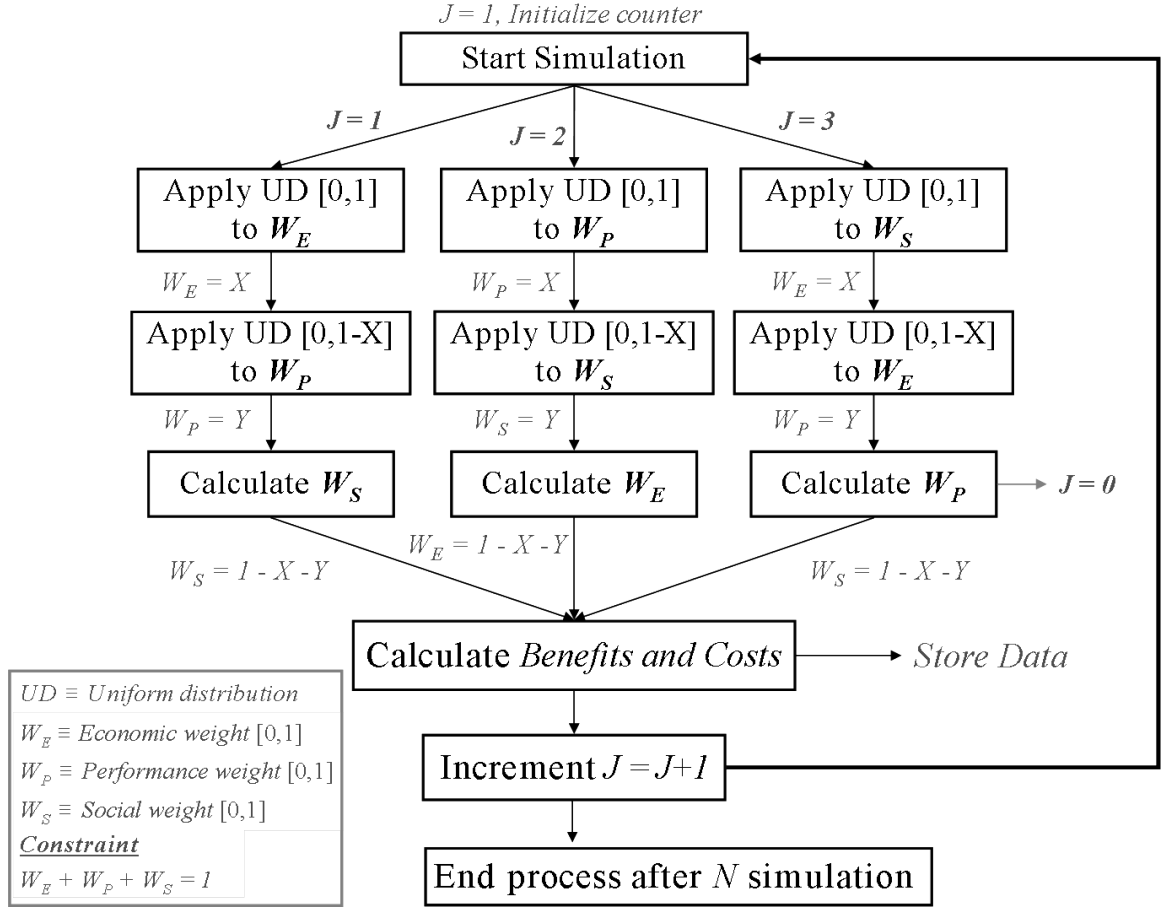


Figure 5.33: Monte-Carlo simulation algorithm.

From this database of results, it is possible to plot the PDF of the input variables, as illustrated in Figure 5.34. From this figure, it can be observed that the frequency of the weight is more important for lower values. This is a consequence of the weight assignment algorithm, since when a weight is randomly chosen to be higher than 0.5, then the sum of the two other weights has to be lower than 0.5. Therefore, it is expected to obtain that decrescendo from lower to higher weight. The fact that all three PDFs have similar distribution constitutes a verification that the Monte-Carlo simulation algorithm works properly.

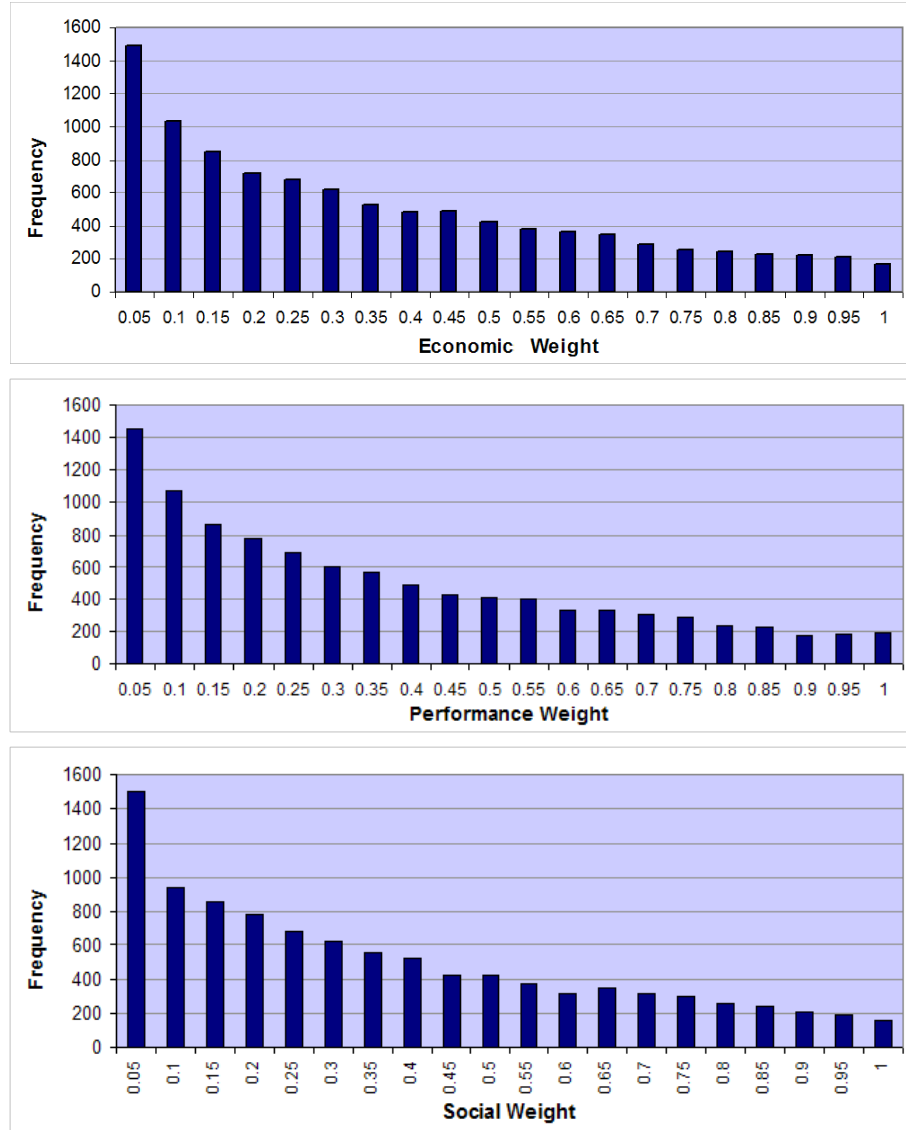


Figure 5.34: Probability distribution function of the input weights.

Associated with these input distributions are the distributions of the tail and cockpit alternatives. These output PDFs are illustrated in figures 5.35 and 5.36. The frequency of the benefits-costs values is calculated based on 50 intervals evenly distributed between the minimum and maximum benefits-costs values. Note that this analysis takes into account the full spectrum of the criterion's weights. In other words, no assumption is made on the preferences of the stakeholders at this stage.

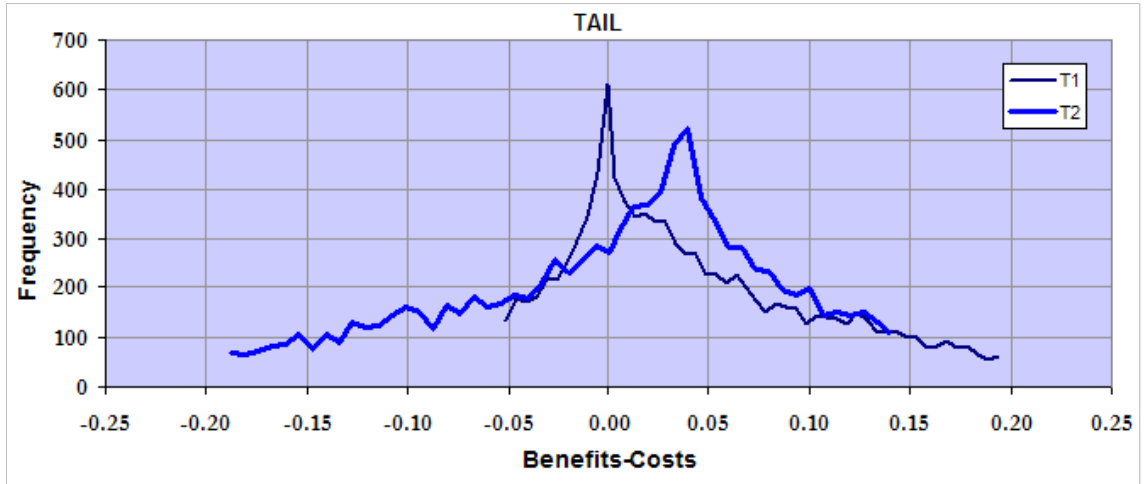


Figure 5.35: Benefits-Costs PDF of tail alternatives.

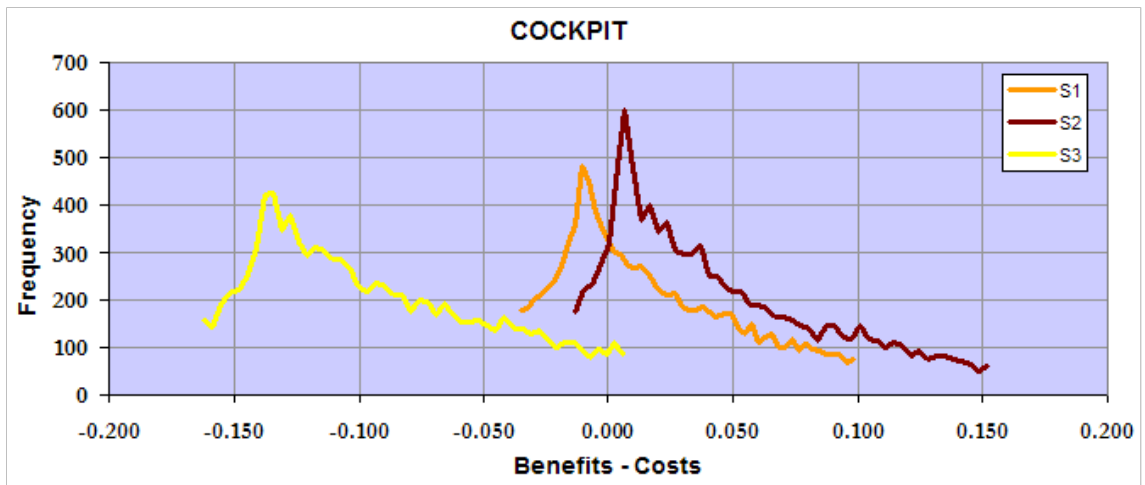


Figure 5.36: Benefits-Costs PDF of cockpit alternatives.

The PDFs of the shape alternatives show the number of times that a given range of benefits-costs value occurs out of the 10,000 simulations. Also the PDFs allow the comparison of the alternatives based on the frequency and the range of benefits-costs. For instance, by comparing the PDFs of tails T1 and T2 in Figure 5.35, it can be observed that the chance of having a negative benefits-costs is higher for T2 than T1. However the peak frequency of tail T2 occurs at a higher benefits-costs value than T1.

The same type of observations can be made for the cockpit alternatives. By looking

at Figure 5.36, it can be seen that for most of the simulation alternative S3 resulted in a negative benefits-costs value. Furthermore, by comparing alternatives S1 and S2, it can be noticed that cockpit S2 has a higher frequency than S1 for all positive benefits-costs value. It implies that regardless of the weighting, if the stakeholders desire a positive benefits-costs value, then the alternative S2 is the appropriate selection. This is significant information that was difficult to deduce from the sensitivity analysis approach.

It is possible to emphasize the robustness of an alternative by transforming the PDF into Cumulative Distribution Function (CDF). A CDF is created from the PDF by summing the area under the PDF curve, and then normalizing by the total area under the curve. The CDFs of the tail and cockpits alternatives are shown in figures 5.37 and 5.38. By normalizing with the total area under the curve, the y-axis of the CDF represents the probability of getting a benefits-costs value below a certain reference fixed by the decision makers. For instance, the probability of having a negative benefits-costs value for the tail alternative is around 30% for T1 and 44% for T2. On the other hand, if the stakeholders desired at least a net tail benefits-costs value of 0.05, the probability of meeting that constraint for tail T1 is of 38% compare to 25% for T2.

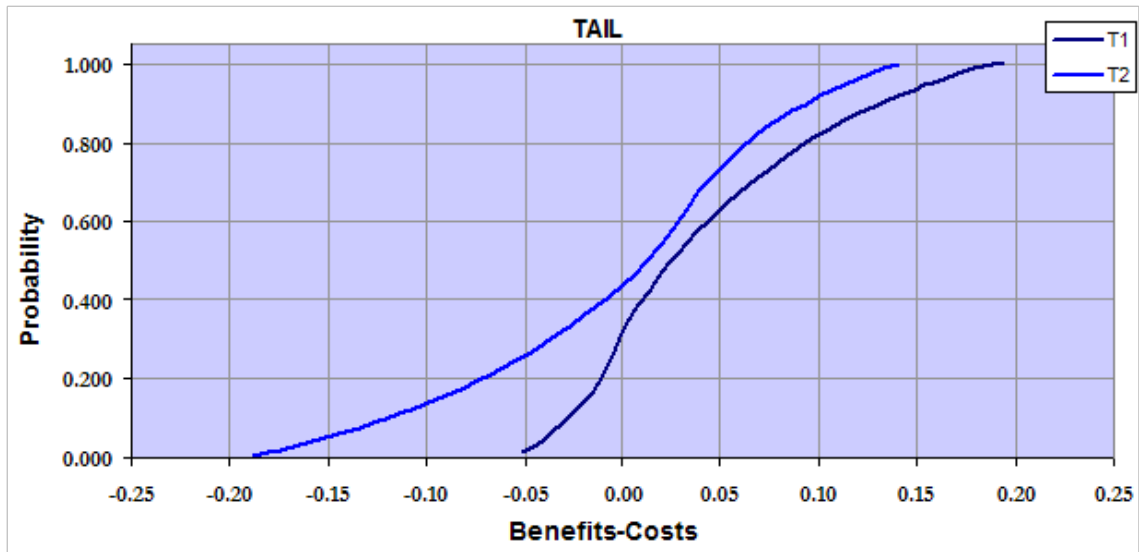


Figure 5.37: Benefits-Costs CDF of tail alternatives.

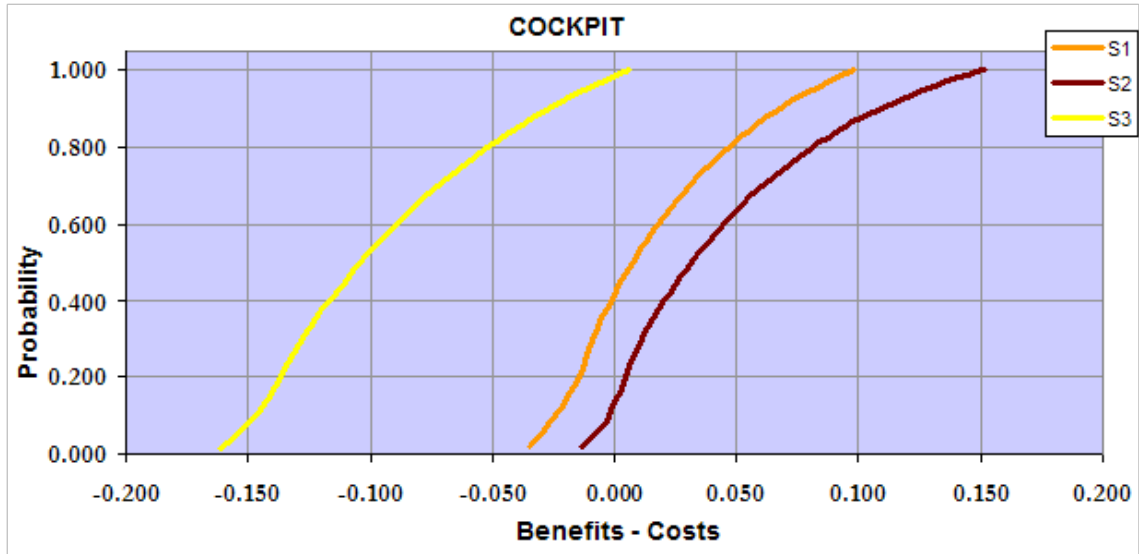


Figure 5.38: Benefits-Costs CDF of cockpit alternatives.

The CDF curves of the cockpit alternatives, in Figure 5.38, makes the PDF information easier to interpret. From this figure it can be deduced that alternative S3 has a 2% probability of resulting in a positive benefits-costs value. When comparing alternative S1 and S2, the results from the Monte-Carlo simulations indicate the probability of having a negative benefits-costs value is 42% for S1 compare to 12% for S2. Consequently, for this analysis based on the predefined weight distribution, alternative S2 has a higher probability of providing a positive benefits-costs value. It can then be considered a robust option for the assumed input distributions. If the assumption is changed on the input distributions, cockpit S2 may not result in a robust solution.

Another way to visualize the results of the Monte-Carlo simulations is to plot the costs as a function of the benefits for each alternative, as shown in figures 5.39 and 5.40. These figures provide more information regarding the shape of the costs/benefits space. For instance, these figures allow the visualization of the minimum and maximum costs and benefits for each alternative. This type of information is also difficult to visualize with the sensitivity analysis, PDF and CDF results.

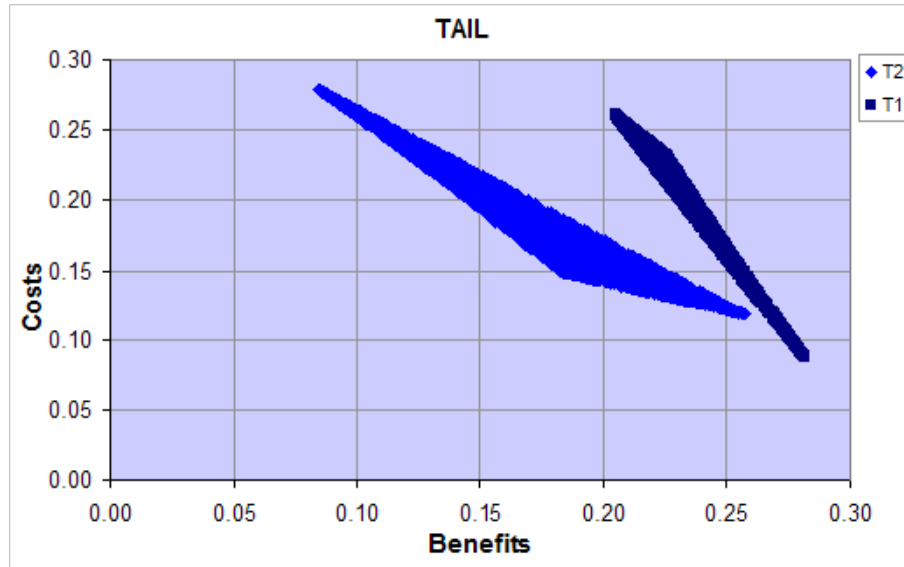


Figure 5.39: Costs vs. Benefits of the tail alternatives.

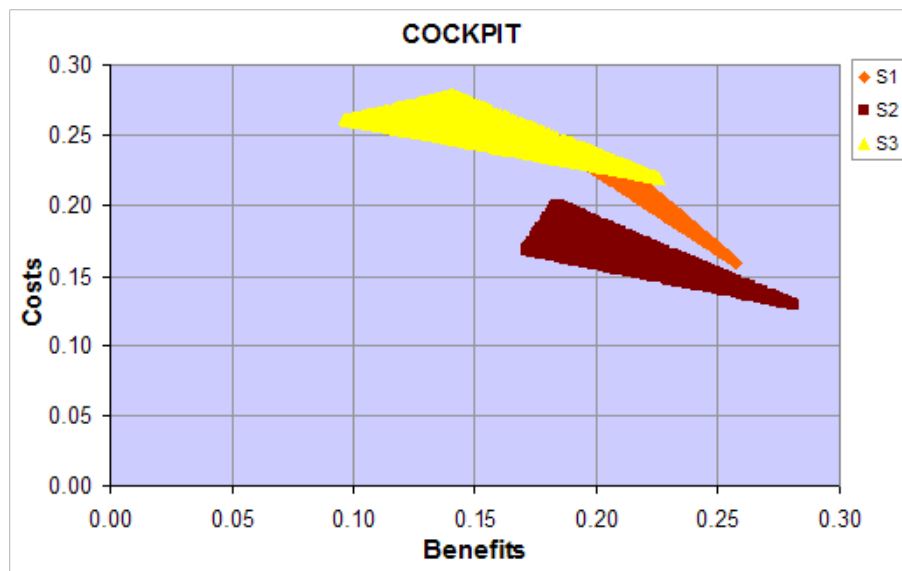


Figure 5.40: Costs vs. Benefits of the cockpit alternatives.

From Figure 5.39, it can be observed that tail T2 has a higher maximum costs and a lower maximum benefits than T1. Also for a fixed cost, T1 always has a higher benefits than T2. More than likely, the stakeholders will be interested in the tail alternative providing maximum benefits at lowest cost, which correspond to alternative T1. By looking at the

Monte-Carlo data, it can be found that the best benefits and lowest costs values for T1 are obtained with a social weight higher than 0.8. But since this Monte-Carlo analysis is taking into account the full spectrum of weight, T1 can be considered more robust than T2 based on the assumed input variables.

For the cockpit alternatives, Figure 5.40, it can be seen that S2 has the highest benefits and the lowest costs of all the other options. These results are also based on a high social weight, greater than 0.8. When the costs of the alternatives become higher than 0.16, then S1 provides more benefits than S2. Looking at these results in the database shows that the S1 benefits and costs values are based on economic weights greater than 0.8.

From these Monte-Carlo analyses, one can notice that the “best” alternatives seem to results from weighting cases where one criterion dominates the other two. This type of weighting scenarios are not frequently used during real decision making problem, since in general some stakeholders may favor one criteria while other stakeholders favor another criteria. Consequently, the process needs to experiment with some weighting scenarios that “limit” the ranges of the input distributions.

The choice of weighting scenario is problem dependent since it needs to be related with the goals of the project. For the presidential helicopter experiment, the main goal is to design a helicopter that looks presidential. Since this requirement is part of a complex systems engineering project, it is assumed that the stakeholders would want to minimize the economic and performance impact of the selected alternatives on the other systems. Consequently, a weighting scenario emphasizing the economic and performance criteria would be more appropriate for this experiment.

An example of a weighting scenario has been created in Table 5.5. It includes a minimum and maximum value applied to the uniform distribution of the criteria.

Table 5.5: Example of weighting scenario.

Criterion weight	Min Value	Max Value
Economic	0.3	0.6
Performance	0.2	0.5
Social	0.1	0.4

Starting the Monte-Carlo simulations with the weighting scenario of Table 5.5 gives the weight distributions shown in Figure 5.41. It can be noticed that most cases are within the imposed boundaries, however since the input variables are dependent on each other, there are some cases where the importance fall outside the pre-defined ranges. The impact of these specific events on the final results can be filtered from the final database.

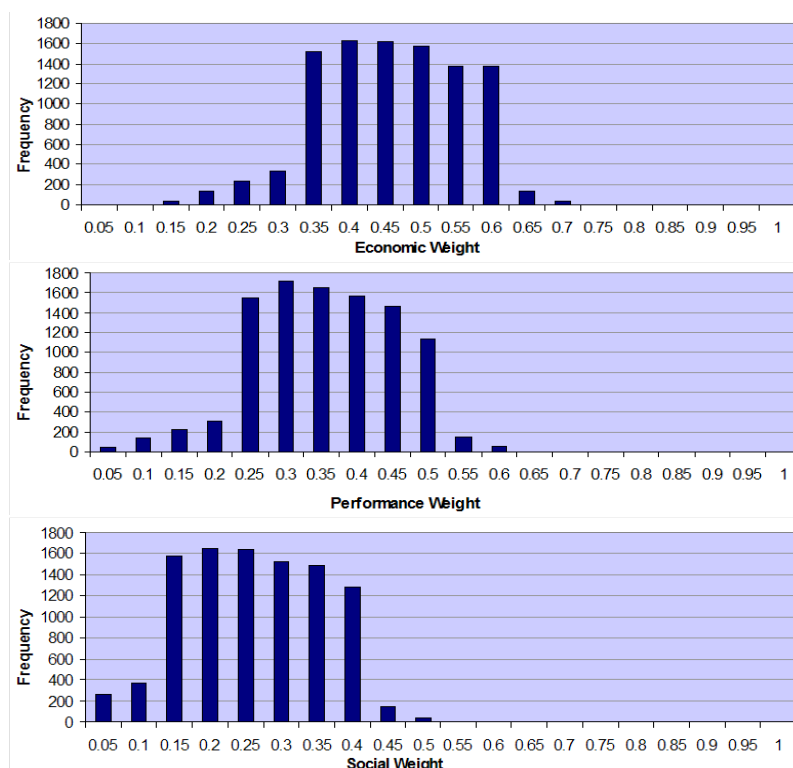


Figure 5.41: Weight distribution from weighting scenario.

These weight distributions give the tail and cockpit PDFs and CDFs of figures 5.42 and 5.43 respectively. It can be observed that the PDFs resulting from this analysis give distributions that resemble a normal distribution. This can be explained by the character more uniform of the input distributions and the Central Limit Theorem [7]. Furthermore, the range of benefits-costs values is greatly reduced compared to the prior Monte-Carlo analysis which varied between -0.18 to 0.18.

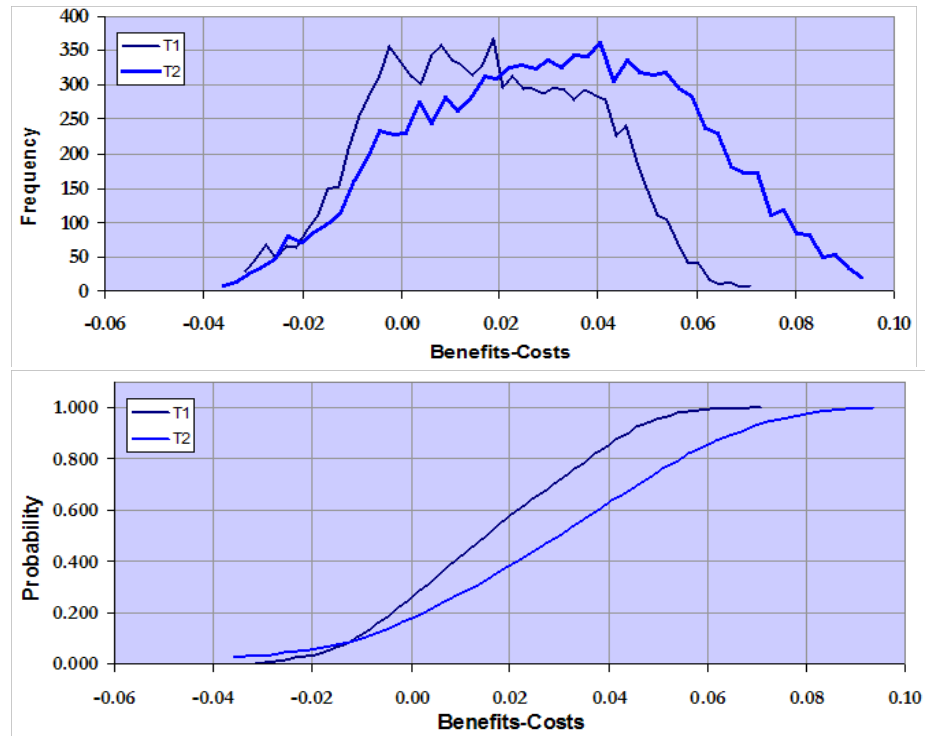


Figure 5.42: Tail PDF and CDF from weighting scenario.

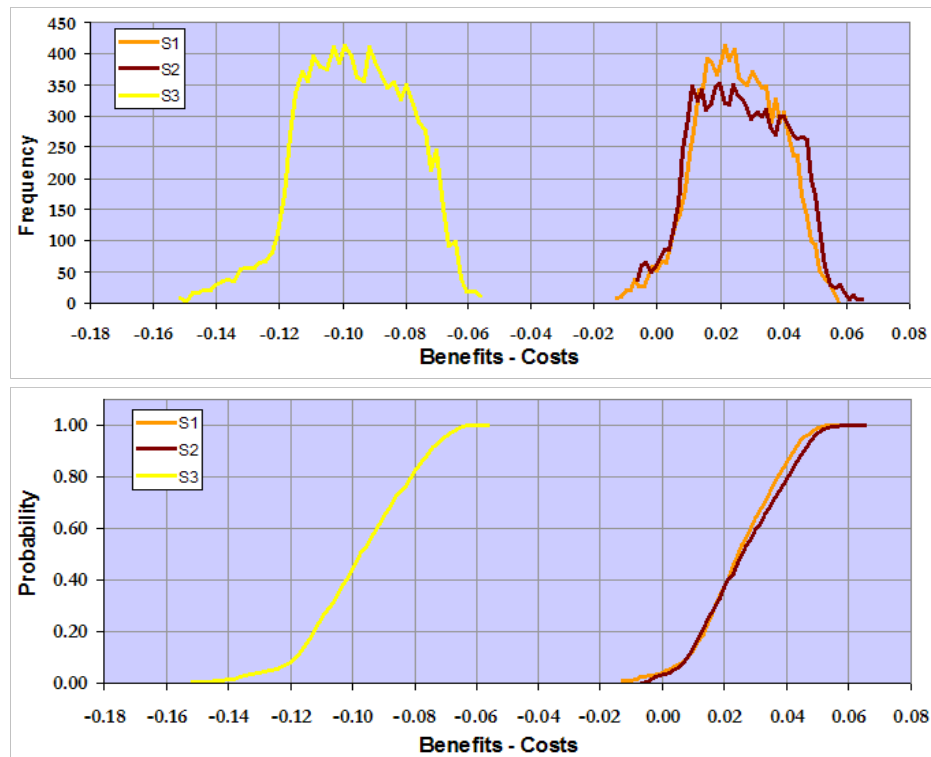


Figure 5.43: Cockpit PDF and CDF from weighting scenario.

Also the ranking of the alternatives is affected by the weighting scenario. It can be seen that when the full spectrum of weight is considered alternative T1 was preferred over T2. However when using the weighting scenario of Table 5.5, the alternative T2 provides better benefits-costs values, as illustrated in Figure 5.42.

For the cockpit alternative, when the full spectrum of weight was considered, alternative S2 gave better benefits-costs values. In Figure 5.43, with the weighting scenario both S1 and S2 give approximately the same values of benefits-costs. To illustrate the difference between these two alternatives, the costs versus benefits plots are created for both the tail and cockpit alternatives as shown in figures 5.44 and 5.45 respectively.

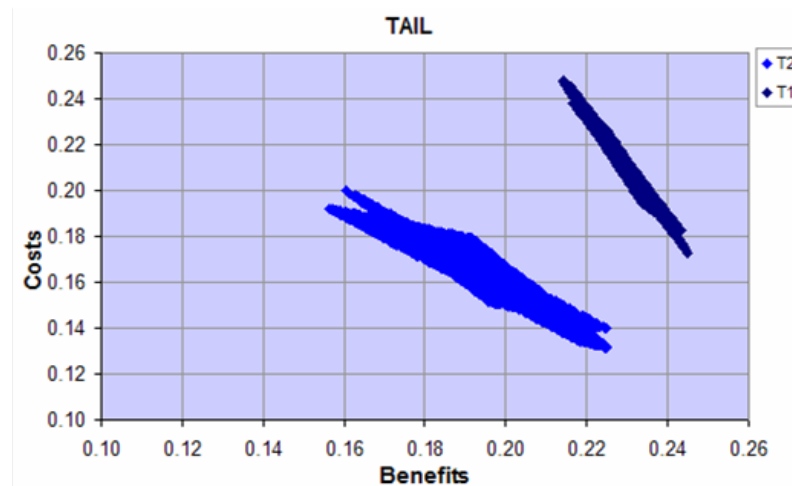


Figure 5.44: Costs vs. Benefits of tail alternative from weighting scenario.

For the tail alternatives, Figure 5.44, it can be seen that T2 has better benefits-costs values primary because of its low cost. Even though T1 provides higher benefits, these values are generally at a higher cost which makes the overall alternative less attractive. However for a given cost value between 0.17 and 0.20, T1 provides higher benefits than T2. This range of costs is driven by high social weight and/or high performance weight. But as soon as the economic weight increases, the cost of T1 increases, the benefits of T2 increase, and consequently T2 has better benefits-costs value.

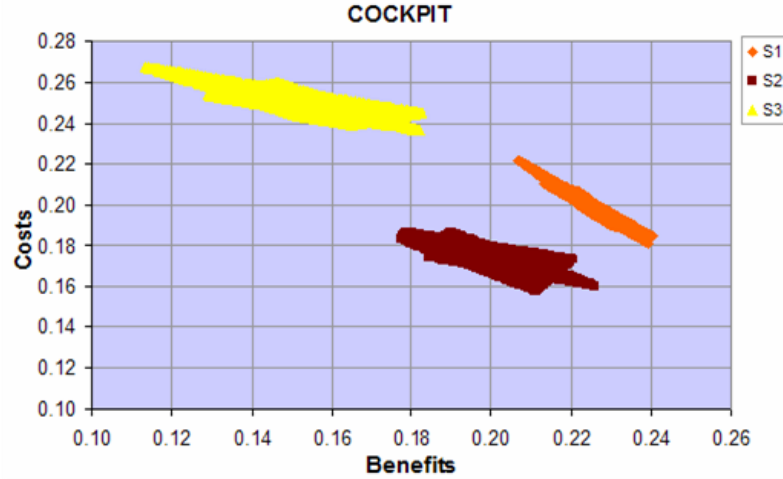


Figure 5.45: Costs vs. Benefits of cockpit with weighting scenario.

For the cockpit alternatives, the CDF curves have shown that alternatives S1 and S2 provide similar benefits-costs value. By decoupling the benefits and costs in Figure 5.45, new information can be gathered for these alternatives. Specifically, it can be seen that in general S2 has a lower cost while S1 provides more benefits at a slightly higher cost. The maximum benefits of S2 are mainly driven by high social weight, while the maximum benefits of S1 are driven by high economic weights.

A number of conclusions can be drawn from the uncertainty analysis and down-selection approach. The uncertainty is present in different forms in the creation of a decision model. For instance, some sources of uncertainty include the lack of knowledge about the system, the complex relationships between systems components, and the large number of criteria to down-select the alternatives are examples of uncertainty that the design team must face during the conceptual design.

The approach described in this section is meant to mitigate the uncertainty by providing a logical framework to decompose the problem complexity and at the same time gather important information to gain a better understanding of the problem. Specifically in this section, the uncertainty is reduced by using sensitivity analysis and Monte-Carlo simulations to analyze the influence of the importance of the criteria on the down-selection of alternatives. The objective of both techniques is to evaluate the robustness of the alternatives by

identifying in which scenarios an alternative is preferred over another.

The sensitivity analysis is a well established technique, reliable and fast. However, it is better suited for a smaller number of criteria, because the results are difficult to interpret as more than two criteria vary at the same time. Consequently, the user has to analyze multiple figures in order to extract the trends and ultimately the importance of the criteria in the down-selection process.

The other technique explored consists of performing Monte-Carlo simulations with uniform distributions applied to the importance of the criteria. This approach takes more time to compute, however more knowledge can be extracted from the PDFs, CDFs and benefits vs. costs figures. For example the results from the CDFs enables the design team to estimate the probability of a given alternative to provide a net benefit. Having such information in hands reduces the uncertainty surrounding the down-selection process and ultimately allow the stakeholders to make better decisions.

5.2.4 Summary of the results and Return to Research Questions and Hypotheses

The presidential helicopter experiment explored the three research areas of the proposed methodology: requirements mapping, uncertainty analysis and requirements down-selection & resource allocation.

For the requirements mapping, hypothesis I (taxonomy) was used to structure the initial hierarchy used for the survey. The results of the survey were collected using both weighted average and pairwise comparison techniques. It has been observed that using both techniques with a small number of alternatives can potentially bias its importance. Consequently, an approach combining a ratio scale of importance with pairwise comparisons would help to reduce the bias.

The second hypothesis referring to the requirements mapping was explored by first using the results of the survey in the SuperDecisions software and also during the creation of the benefits and costs model. The Analytic Network Process and Analytical Hierarchy Process provide the flexibility to represent the problem in terms of a network or hierarchy. It also enables the use of a pre-defined ratio scale to perform the pairwise comparison.

A limitation of the SuperDecisions software is related to the synthesis of the alternative cluster. SuperDecisions only allows for one cluster of alternatives which influence the final importance of the alternatives during the synthesis of the hierarchy. Consequently, a hybrid approach was created combining the flexibility of the software with a decoupled synthesis process.

The down-selection of alternatives used this hybrid approach in the creation of a Benefits/Costs model (Hypothesis IV). In lean thinking, benefits and costs models can be used to establish the value of an alternative [195]. In this experiment, the value of an alternative represents how well it is answering the criteria of the hierarchy. This down-selection process also offers the flexibility to use important stakeholders criteria. For the presidential helicopter experiment, the performance, economics and social criteria were defined in a hierarchy taking into account the stakeholders, resources and systems alternatives. Then depending on the preferences of the decision makers, some alternatives were deemed more robust than others.

The uncertainty surrounding the design of a new project makes it difficult for the decision makers to have a clear idea of their preferences early in the design. Consequently two uncertainty analysis techniques were explored to define the robustness of the alternatives with respect to the criteria. This analysis concluded that the Monte-Carlo simulations were more suited to visualize and extract knowledge from the results of the benefits-costs models.

The lessons learned from the presidential helicopter experiment with respect to the research areas will be implemented in the UAV design application.

5.3 Second Experiment: Unmanned Aerial Vehicle Requirements Analysis

One of the motivations for this research is to perform requirements analysis for complex systems including large design freedom, which implies a large number of requirements at the conceptual design stage. Unmanned Aerial Vehicles are good examples of such complex systems since they can be used to perform a wide spectrum of missions in many different operating conditions.

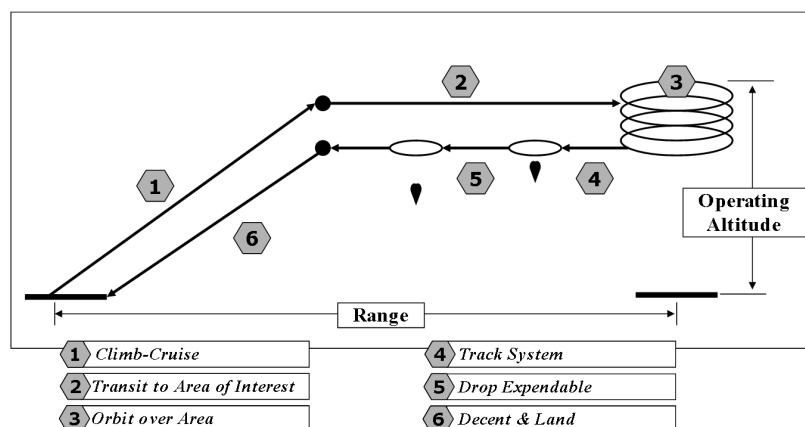
One of the UAV applications studied by NASA, within the Environmental Research Aircraft and Sensor Technology (ERAST) program, is to use a High Altitude Long Endurance (HALE) UAV to track a hurricane from its genesis to its landfall [134, 135]. During this mission the vehicle is expected to gather scientific measurements to improve the strength and trajectory predictions of a storm system.

This experiment is meant to provide insights on the applicability of the proposed methodology to the design of complex systems. In practice, a design team would perform the six steps of the methodology, however for this research the objective is to assess how the hypotheses described in section 4.1 address the research questions formulated during the research scope definition (Chapter 2).

5.3.1 Step 1: Classify the Expectations

The first step is to gather and classify information regarding the new hurricane tracker UAV. This step involves the collection of both qualitative and quantitative information. Note that this experiment does not assume any RFP, the stakeholder expectations are gathered from a notional mission profile and systems architecture. Also this experiment assumes a fixed wing vehicle, no specific rotary wing or lighter than air functions, MoEs and alternatives are considered.

The mission profile used for this experiment is inspired from the NASA technical report TP-2007-214861 [135]. Figure 5.46 illustrates this notional mission profile as well as the expected physical area of operation of the UAV.



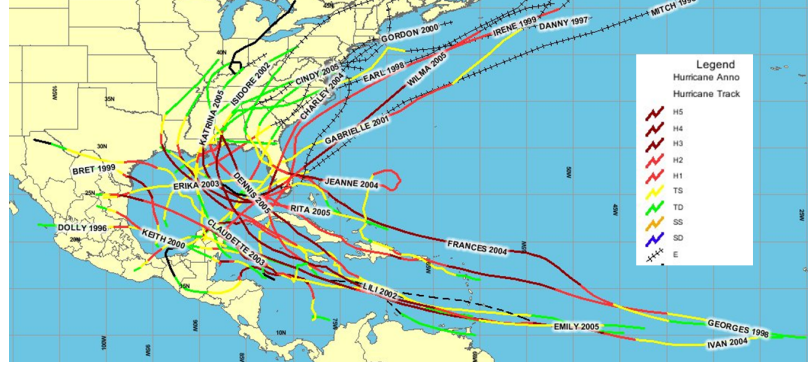


Figure 5.46: UAV mission profile [135] & historical hurricane trajectories [136].

From an operational perspective, hurricane tracks provide a representation of the range (distance) and operational latitude (operating conditions) expected from the UAV. Also the hurricane historical data can be useful to define the endurance and the ground velocities (cruise, endurance) of the vehicle. From a system perspective, a notional system architecture is defined in Figure 5.47 to provide the foundation for the identification and definition of systems functions.

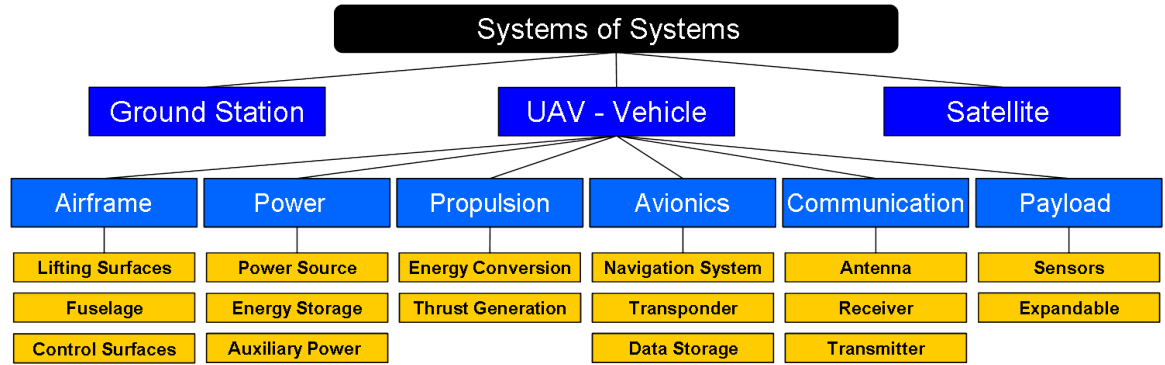


Figure 5.47: General UAV system architecture.

Referring to the requirements taxonomy, the concept of operations and systems elements can be classified under the first three levels of the taxonomy as shown in Figure 5.48.

In this specific experiment, since no information is directly provided by the stakeholders there are no “*Specified*” expectations. In addition, no regulatory or corporate expectations will be introduced in order to have a manageable number of requirements and therefore focus on the application of the research hypotheses. The next activity is then to identify the

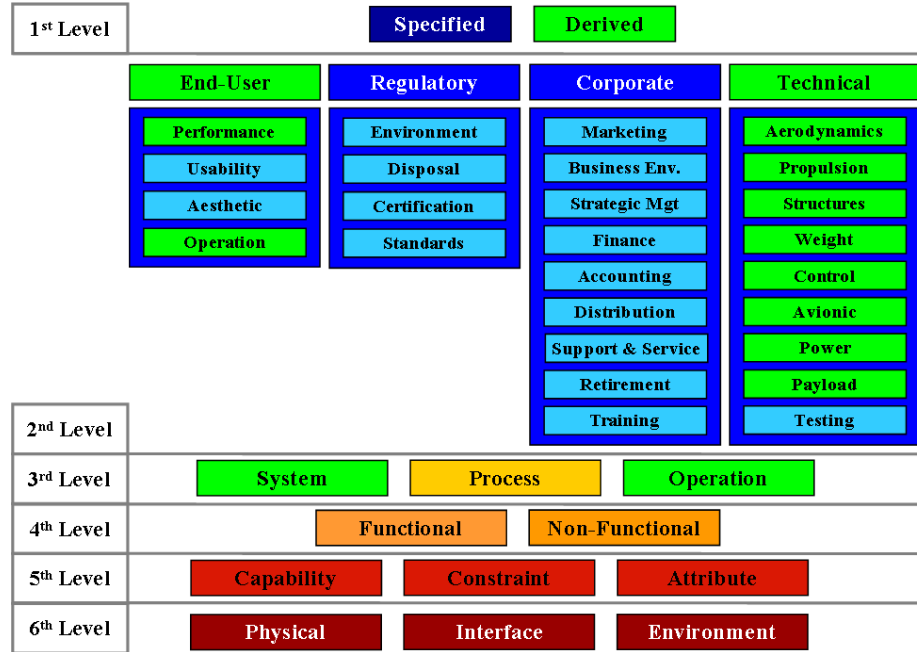


Figure 5.48: Classification of the operational and systems elements.

functions (level 4) and the measures of effectiveness (attribute - level 5) that will be used for the creation of the mapping in Step 2 of the proposed methodology.

The operational and systems functions shall be defined as a “*actor-verb-object*” statement. The operational functions are related to an operational scenario whereas the systems functions are linked to the top-level system. Table 5.6 lists the operational functions with their respective mission segment and measures of effectiveness.

Table 5.6: Concept of operations functions and measures of effectiveness.

MISSION SEGMENT	FUNCTION (<i>actor-verb-object</i>)	MEASURE OF EFFECTIVENESS		
1 - Takeoff	UAV has to takeoff	1 - Runway dimension		
2 - Climb	UAV climbs to optimum altitude	1 - Climb rate	2 - Climb altitude	3 - Structural stress
3 - Transit to area of interest	UAV transits to area of interest	1 - Cruise Speed	2 - Cruise altitude	3 - Range
4 - Orbit over area	UAV orbits over area of interest	1 - Time on station	2 - Endurance altitude	3 - Endurance speed
		4 - Latitude Range	5 - Rate of Sink	6 - Collect Data
		7 - Store Data		
5 - Track storm system	UAV tracks object of interest	1 - Tracking speed	2 - Tracking altitude	
	UAV modifies flight path	3 - Max turn rate		
6 - Drop expendables	UAV drops expendable	1 - Drop speed	2 - Drop altitude	
<i>Return to base</i>	UAV transits from area of interest	<i>1 - Cruise Speed</i>	<i>2 - Cruise altitude</i>	<i>3 - Range</i>
7 - Descend	UAV descent to base	1 - Descend rate		
8 - Land	UAV lands at base	1 - Landing speed	2 - Runway dimension	

In this table, there are two measures of effectiveness that are not directly related to the UAV but to the sensor package. Since the main function of the vehicle is to gather scientific

data, the MoEs “collect” and “store” data are considered to be embedded in the concept of operations. Also the mission segment “*Return to base*” will be merged in the mapping with the segment “*Transit to area of interest*” since they are associated with the same MoEs, which assumes a non-disposable vehicle.

The next task is to enumerate the systems functions and MoEs from the general UAV system architecture, Table 5.7.

Table 5.7: System functions and measures of effectiveness.

SYSTEM	FUNCTION (<i>actor-verb-object</i>)	MEASURE OF EFFECTIVENESS		
1 - Airframe	Airframe provides sufficient lift	1 - L/D	2 - $C_{L\ MAX}$	3 - Wing Span
	Airframe carries payload	4 - Wing Area	5 - Wing Aspect Ratio	
2 - Propulsion	Energy is converted into mechanical work	1 - Weight	2 - Internal volume	3 - Wing loading
3 - Fuel	Fuel provides energy to systems	1 - Prop. Specific energy	2 - Conversion efficiency	3 - Energy consumption
4 - Power	Power systems provides electrical energy	1 - Fuel specific energy		
5 - Avionics & CTRL	Avionics determine vehicle state variables	1 - Power Specific energy		
	Avionics stores information	1 - Positioning accuracy		
6 - Communication	Comm. transmit and receive information	1 - CPU speed		
		1 - Comm. power	2 - Comm. Bandwidth	3 - Antenna size
7 - Payload	Payload sustains environment	4 - Comm. Availability	5 - Comm. robustness	
	Payload collect data	1 - Operating conditions		
		1 - Payload power	2 - Sensor resolution	3 - Acquisition rate
8 - Ground Station (GS)	GS monitor the vehicle	4 - Field of view		
9 - Expendable Payload		1 - Line of Sight range	2 - Satellite range	
	Expendable collect vertical measurements	1 - Number of expendable units		

For a new project, the level of detail of the systems functions and MoEs varies depending on the experience and knowledge of the design team members. As the level of knowledge increases, the systems can be expected to be broken down into more sub-systems with their associated functions and MoEs. The elements listed in Table 5.7 represent a sample of the possible functions and MoEs that can be used, and in the context of this research they are deemed sufficient to demonstrate the ability of the proposed methodology to answer the research questions.

The next step of the proposed methodology consists of using the operation and systems information identified in this step to create the requirements mapping.

5.3.2 Step 2: Create Requirements Mapping

The activities required for the requirements mapping are illustrated in Figure 5.49. The first three activities (A, B & C) were performed in Step 1 to demonstrate how the taxonomy is used to classify the information. It is important to note that the proposed methodology

is composed of iterative activities, allowing new expectations, functions and MoEs to be derived and added at any time in the process.

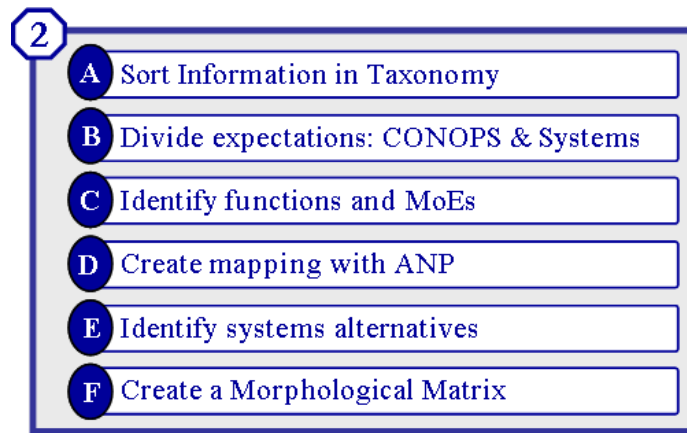


Figure 5.49: Step 2: Activities involve in the requirements mapping.

The first three activities of Step 2 were performed in the previous section to demonstrate how the taxonomy can be used as a framework to classify the information. Therefore the first activity of this section is to create a mapping between the operational and systems elements using ANP (*activity D*). To highlight the differences between the House of Quality (HoQ) and AHP/ANP mapping, Figure 5.50 illustrates an example of HoQ relationship matrix including operational and systems MoEs.

In this example of Figure 5.50, the symbols “*x*” within the relationship matrix indicate that a relationship between a system and an operational MoE. Note that the strength of the relationship is neglected at this time. Typically in the HoQ process the design team would start with the first operational MoE and go through all the system MoEs to identify and define relationships.

In the AHP/ANP process, the comparisons between the operational and system MoEs are performed through the hierarchy or network model. The bold contours within the relationship matrix of Figure 5.50 signify the presence of a higher level relationship between a mission segment and a system, for example “*Orbit over System*” and “*Airframe*” is a higher level relationship defined in the AHP/ANP framework. These higher level relationships are not typically assessed in the HoQ process.

A schematic diagram of the AHP/ANP mapping is represented in Figure 5.51.

SYSTEM		AIRFRAME								PROPULSION		FUEL	POWER	AVIONICS	COMMUNICATION				Fixed-PAYLOAD							
		1-Vehicle CL/CD	2-CLmax	3-Total Weight	4-Internal Volume	5-Wing Span	6-Wing Area	7-Wing-Aspect-Ratio	8-Wing-Loading	1-SpecificPower	2-Conv-Efficiency	3-Energy Consumption	3-Fuel Spec. Energy	2-Elect-Specific-Energy	3-CPU Speed	4-Positioning Accuracy	2-Comm Power	3-Comm Bandwidth	4-Antenna Size	5-Antenna Weight	6-Comm. Availability	7-Comm-Robustness	4-Operating Conditions	5-Resolution	6-Acquisition Rate	7-Field of View
MISSION SEGMENT	1-TAKEOFF	x	x	x	x	x	x	x	x	x	x	x														
	2-CLIMB	x	x	x			x	x	x	x	x	x					x			x			x			
	3-TRANSIT TO/FROM AREA	x	x	x		x		x	x	x	x	x									x					x
4-ORBIT OVER SYSTEM	1-Cruise Speed	x	x	x			x	x	x	x	x	x									x		x	x	x	
	3-Range	x	x	x	x			x		x	x	x	x			x	x		x		x	x	x	x		
	1-Time on Station	x	x	x	x			x		x	x	x	x				x				x	x	x	x		
5-TRACK SYSTEM	2-Endurance Altitude	x	x	x				x		x	x	x					x				x	x	x	x		
	3-Endurance Speed	x	x	x				x		x	x	x				x				x	x	x	x			
	4-Latitude Range	x	x	x				x		x	x	x				x										
	5- Max Rate of Sink															x										
	6-Collect Data															x	x	x	x	x	x					
	7-Store-Data																x	x	x							
	1-Tracking speed	x					x	x	x		x	x	x			x	x	x			x	x				
6-DROP EXPANDABLE	2-Tracking Altitude	x	x	x			x	x	x	x	x	x					x	x		x	x					
	3-Max Turn Rate	x	x	x				x	x	x	x	x				x										
	1-Drop Speed	x						x	x	x	x	x														
7-DESCEND	2- Drop altitude	x						x	x	x	x	x				x	x	x		x	x					
	1-Descend Rate	x		x			x	x	x							x	x									
	1-Landing Speed		x																							
8-LANDING	2-Runway Dimensions	x				x	x	x	x	x						x				x	x					

Figure 5.50: Mapping representing relationship matrix of HoQ.

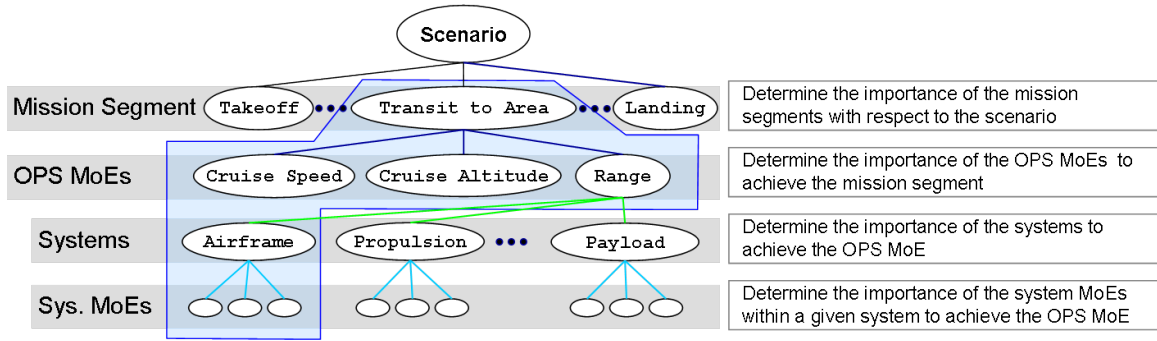


Figure 5.51: Schematic Diagram of AHP/ANP mapping.

It can be noticed that in the AHP/ANP mapping the different level includes all the operational and system elements from the mission segments to the system MoEs. This continuous hierarchical mapping implies that the importance of the systems MoEs are influenced by the pairwise comparisons performed at every level of the hierarchy.

As illustrated in Figure 5.51, the first level of the hierarchy is used to determine the importance of the mission segments with respect to a given operational scenario. The second level of the hierarchy determines the importance of the operational MoEs for each mission segment. The third level of the hierarchy determines the importance of the systems for each operational MoE, and the last level of the hierarchy determines the importance of the system MoEs for each system and operational MoE. The last level thus takes into account two higher levels, for instance the relative importance of the airframe MoEs will vary depending if they are based on cruise speed, cruise altitude or range.

The schematic diagram of AHP/ANP mapping is then translated into clusters and nodes created into the SuperDecisions software, as illustrated in Figure 5.52.

In SuperDecisions the mission segments are modeled with clusters including the operational MoEs as node elements. The operational MoEs include a “*subnet*” which can be either a hierarchy or network that maps each operational MoE with the systems and systems MoEs. The arrows between clusters indicate the presence of relationships between one or more node elements, and the directionality of the arrow represents the path from a higher to a lower level of the mapping. The software also features an option to quickly visualize the relationships between the node elements, or the relationships can be visualized in the

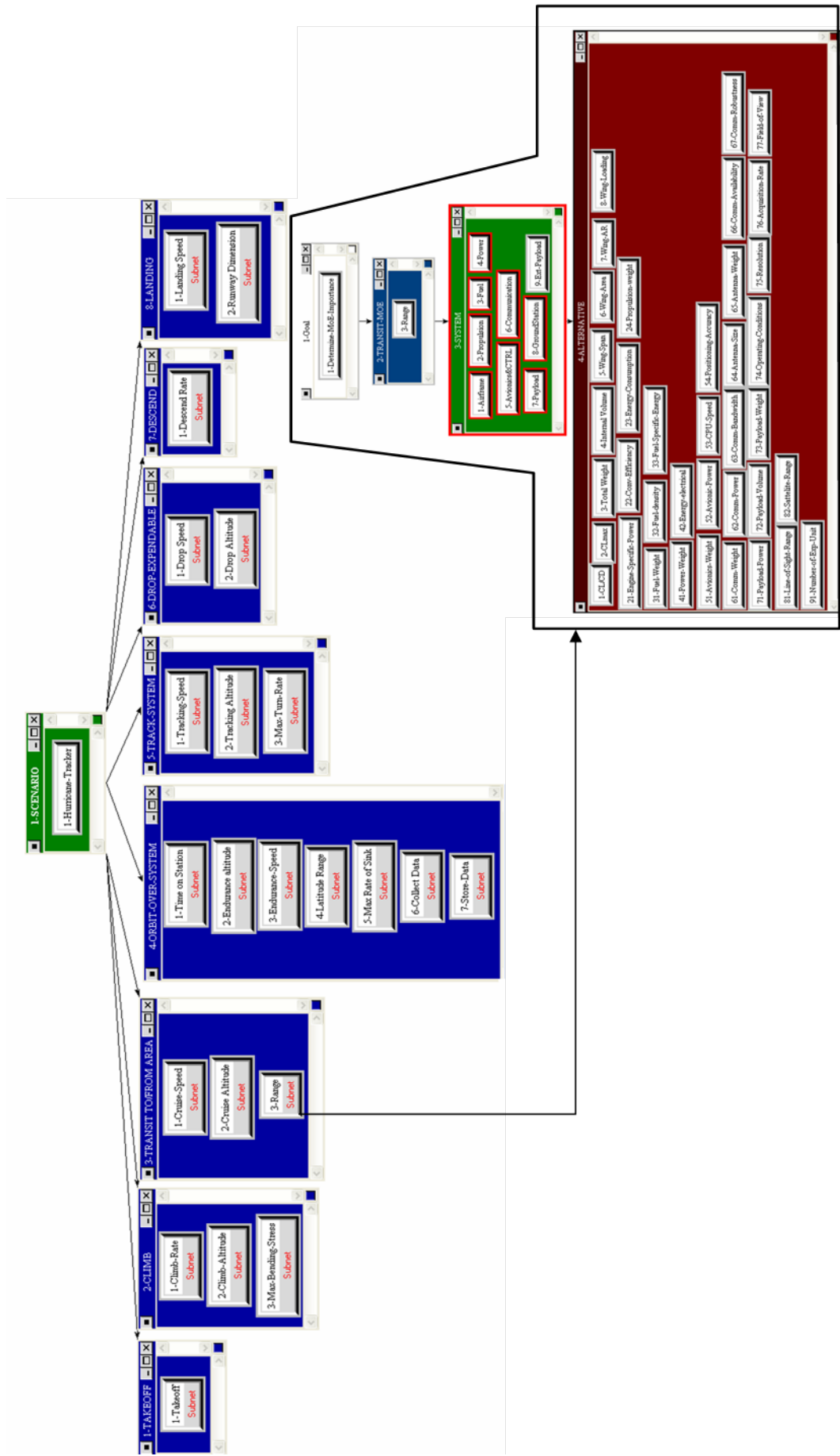


Figure 5.52: AHP / ANP Mapping in SuperDecisions

unweighted matrix as described in section 4.2.3

Consequently in *activity D* of the requirements mapping, the design team can use the SuperDecisions software to identify and create links between the elements of the hierarchical model. Since SuperDecisions is an object-oriented software, links between nodes can be dynamically created or removed, which facilitates the creation of the mapping and at the same time improves the understanding of the problem. The relationships are then used in Step 3 of the proposed methodology (section 5.3.3) to determine the relative importance of the elements included in the hierarchical model.

5.3.2.1 Initial Down-Selection of Systems Alternatives

The last two activities of the requirements mapping are related to the identification of system alternatives (E) and the creation of an incompatibility matrix (F). The concept of morphological analysis is used in this research to identify and classify systems alternatives. Morphological analysis was developed by Zwicky in the 1950's; the objective of this process is to structure a problem into categories and identify potential alternatives for each category [207]. The categories and alternatives are stored in a matrix referred as morphological matrix or matrix of alternatives.

In November 2005, the NASA High Altitude Long Endurance Aircraft (HALE) conceptual design team, including 13 experts, participated in a design workshop at the Georgia Institute of Technology Aerospace Systems Design Laboratory [119]. The objective of this workshop was to prioritize current and future UAV's technologies. While reviewing the requirements for a HALE UAV, the team constructed an Interactive Reconfigurable Matrix of Alternatives (IRMA) based on the functional decomposition of a hurricane-tracking mission. This IRMA is illustrated in Figure 5.53.

One HALE vehicle configuration implies the selection of one alternative per row of the matrix. Consequently, for the IRMA of Figure 5.53 there are more than 5.5×10^{97} possible configurations of alternatives. Assuming that the design team is able to evaluate one alternative per second, it would take 1.76×10^{90} years to evaluate every configuration. A first down-selection of alternatives is required, since the design team has a limited amount

of time to select a feasible and viable system configuration.

In Reference [135], the team eliminated alternatives based on low Technology Readiness Level (TRL), high risk or poor safety characteristics. The TRL scale measures the maturity of the technology from a value of 1 (“*basic principles observed and reported*”) to 9 (“*actual system 'flight proven' through successful mission operations*”) [113]. Therefore, a low TRL level implies that more funding and time are required for the development of the technology. In the life cycle analysis of the hurricane-tracker UAV the design phase was assumed to be 2 years, which emphasized the use of matured technologies. For the risk and safety criteria, the down-selection takes advantage of the experience of the experts with respect to some of the alternatives.

Based on the defined CONOPS and experience of the experts, the team selects one alternative per category of the IRMA, as illustrated in Figure 5.54. By eliminating and selecting alternatives, the number of configurations dramatically decreases to a more manageable number. In this case, the reduced set of alternatives corresponds to 180 possible combinations, and all these configurations could be analyzed in around 7-8 days by assuming that one combination is analyzed per hour.

A subset of the initial IRMA is used in this section to demonstrate the implementation of the proposed methodology. For this research, it is assumed that the UAV experiment explores the power and propulsion system alternatives. Figure 5.55 shows the resulting morphological matrix of the propulsion, fuel and power systems. Also note that for this experiment, all the engine types, except the diesel engine, are being used exclusively with liquid hydrogen (LH2).

From the morphological matrix it can be noticed that more than one system MoE can be associated with one category of the matrix. For example in the *Engine type* category, two system MoEs are associated with five alternatives. On the other hand, for the power system more than one category is required to map the alternatives with one system MoE (power specific energy).

Therefore by assuring that the morphological categories are as independent as possible, the overall system can be “*built*” by selecting one alternative per category. The number

Mission	Altitude			Time On station (i.e., chase or loiter time)			Computational Analysis Time		
	Mission Radius			Location and time of year (energy availability)					
	Station keeping accuracy			Critical Ground Speed			One Run per Second: 1.75084788E+90 Years		
	Wind Tol: Launch and Recovery			Wind Tol: Sustained			One Run per Minute: 1.053050873E+92 Years		
Mission	Wind tolerance: Uniform			Gust tolerance: Non-uniform			One Run per Hour: 6.318305238E+93 Years		
	Service Life			Expendable Payload					
	Fixed payload			Weather			Disaster monitoring		
	Completion rate			Mission operational concepts					
Power and Propulsion	Operating environment			Runway length			Tip-joined multi-vehicle		
	Recovery Launch			Runway width					
	Power source			Energy conversion					
	Energy storage			Thrust generation-propulsions					
Configuration	Auxiliary power generation			Fuel			Fuel Cell + Electric Motor Hybrid		
	Variable Geometry			Rotorcraft			Chord		
	Fixed Wing			Airship (LTA)			Three surface + B Powered Balloons		
	Detect and Avoid			Health management			Laser		
Sensors, Avionics	Flight control sensors			Command mission termination systems			Autonomous safe		
	Command link: line of sight			Command link: beyond line of sight			Pyrotechnic		
Control	Climb & Descent			Cruise			Single down-dual up		
	Take-off and landing			Data Link: line of sight			LEO		
Data Link	Data Link: beyond line of sight			Data Link: beyond line of sight			Single down-dual up		
							LEO		

Figure 5.53: IRMA initial HALE alternative configurations.

Interactive Reconfigurable Matrix of Alternatives					Possible Combinations		
					180		
Mission	Altitude	>13 km	>18 km	>20 km	Unlimited	Computational Analysis Time One Run per Second: 3.000000 Min One Run per Minute: 3.000000 Hrs One Run per Hour: 7.500000 Days	
	Time On station (i.e., chase or loiter time)	~7 days	~30 days	~100 days	~1000 km		
	Mission Radius	~3500 km	~5000 km	~7000 km	Unlimited CONUS		
	Location & time of year (energy availability)	Tropical, Hurr. Season	Tropical, Year Round	Unlimited CONUS	250 kph		
	Station keeping accuracy	~1 km	~5 km	~10 km	200 kph		
	Critical Ground Speed	105 kph	150 kph	200 kph	50 kph		
	Wind Tol: Launch and Recovery	10 kph	25 kph	50 kph	~150 kph		
	Wind Tol: Sustained	<100 kph	<100 kph	<100 kph	~200 kph		
	Gust tolerance: Uniform	<7.5 mps	<15 mps	<22.5 mps			
	Gust tolerance: Non-uniform	TBD1	TBD2	TBD3			
	Service Life	~3000 hrs	>7500 hrs	>10000 hrs	>40000 hrs		
	Expendable Payload	Droptones	Mini-UAV	Drop and UAV	None		
	Fixed payload	Broadband	Cell phone	Hurricane package	Hurricane-Doppler		
	Weather	Standard Day	Near all weather	All weather	Disaster monitoring		
	Power and Propulsion	Completion rate	>90%	>95%	>99%		>99.9%
Mission operational concepts		Aux. powered deployment	Refueled in flight	Single vehicle	Formation flight	Serial flight	
Operating environment		Mil Std 210 Std Day	Mil Std 210 Cold Day	Mil Std 210 Hot Day	Mil Std 210 Tropical Day	Tip-joined multi-vehicle	
Runway length		<150 m	<1500 m	<2000 m	circular		
Recovery		None	Wheeled Runway Landing	Parachute	Stand alone		
Launch		Towed	Wheeled Runway Launch	Dolly	Parasail		
Runway width		<45 m	<60 m	circular		Skid gear	
Power source		None (implies fuel)	Beamed	Solar		In air recovery	
Energy conversion		IC Engine	Gas Turbine	None	Primary Battery		
Energy storage		None	Altitude	Battery	Photovoltaic+Electric Motor	Nuclear	
Thrust generation-propulsions		Propeller	Rotary Wing	Jet	Fly wheel	Stirling Heat Engine	
Auxiliary power generation		Mech. power extraction	Electrical Power Extraction	Bleed extraction	Rocket	Regen. Fuel Cell	
Fuel		None	Hydrocarbon	Hydrogen	Stand alone	Flapping wing	
Configuration		Variable Geometry	None	Span	Sweep	Dihedral	Chord
		Rotorcraft	None	Helicopter	Autogiro	Tiltrotor	Aux surfaces
	Fixed Wing	None	W-B-7/C	Bl-plane	All wing	Three surface + B	
	Airship (LTA)	None	Dirigible	Blimp	Hybrid	Powered Balloons	
Sensors, Avionics	Detect and Avoid	Radar	Chase	EO	IR	Ultrasonic	
	Health management	None	Federated	Integrated		Laser	
Command	Flight control level	Flight control level	Precise pointing	GPS only	GPS + compass		
	Command mission termination systems	None	Controlled Return	Controlled Ditch	Parachute	Pyrotechnic	
Control	Command link: line of sight	None	Single channel	Dual channel	Freq hopping	Single down-dual up	
	Command link: beyond line of sight	None	Relay	HF	GEO	LEO	
Data Link	Climb & Descent	Controlled: LOS	Controlled: Non-LOS	Controlled: pitch roll rate	Semi-auto: pre-programmed	Autonomous safe	
	Cruise	Controlled: LOS	Controlled: Non-LOS	Controlled: pitch roll rate inputs	Semi-auto: pre-programmed	Mil band	
Data Link	Take-off and landing	Controlled: LOS	Controlled: Non-LOS	Controlled: pitch roll rate inputs	Semi-auto: pre-programmed	VLF	
	Data Link: line of sight	None	Single channel	Dual channel	Semi-auto: heading, alt.	Fully auto: IVHM	
Data Link	Data Link: beyond line of sight	None	Relay	Dual channel	Semi-auto: heading, alt.	Fully auto: IVHM	
		None	Relay	Dual channel	Single down-dual up	Mil band	

Figure 5.54: IRMA Down-Selection of alternative configurations.

SYSTEM	SYSTEM MoE	ALTERNATIVE				
PROPULSION		1	2	3	4	5
Engine Type	Specific Energy & Energy consumption	IC Engine + turbo	Gas Turbine	Electric Motor	Stirling	Diesel
Conversion Type	Conversion Efficiency	Fixed Pitch Prop	Variable pitch Prop	Jet		
FUEL						
Fuel Type	Fuel Specific Energy	Hydrocarbon	H2 (liquid)			
POWER						
Power option		Not Regen	Renenerative	Hybrid		
Primary energy storage	Power specific energy	Battery	Fuel Cell			
Secondary energy storage		Solar	Beam	altitude	Flywheel	

*IC = Internal Combustion

Figure 5.55: Morphological matrix of propulsion, fuel and power systems.

of possible combinations that can be used to build the overall system can be determined by multiplying the number of alternatives for each category. For the morphological matrix of Figure 5.55, assuming that all the alternatives are compatible, there are 720 possible configurations. That number rapidly increases as more systems or categories are added to the matrix.

However the alternatives are not always compatible, for instance a power system can either be *non-regenerative*, *regenerative* OR *hybrid*. Incompatibilities between alternatives reduce the number of system combinations. The incompatibilities are commonly stored in a matrix, which would allow an algorithm to determine the incompatible alternatives from previous alternatives selection, and consequently only allow the construction of compatible systems. Figure 5.56 illustrates the incompatibility matrix for the propulsion, fuel and power systems. In this figure the incompatibilities are represented in red.

It can be expected to have more incompatibilities close to the main diagonal of the matrix, since the alternatives are mutually exclusive. By taking into account the incompatibilities, the number of combinations is reduced from 720 to 138. Even though this number is more manageable, it is still highly challenging to investigate in detail 138 combinations of alternatives.

The challenge of addressing a large number of alternative combinations is discussed in steps 4 & 5 of the proposed methodology, section 5.3.4. That section will also discuss the complete mapping between the systems MoEs and the systems alternatives based on a Benefits, Costs and Risks model.

		IC Engine + turbo	Gas Turbine	Electric Motor	Stirling	Diesel	Fixed Pitch Prop	Variable pitch Prop	Jet	Hydrocarbon	H2 (liquid)	Not Regen	Renegerative	Hybrid	Battery	Fuel Cell	Solar	Beam	altitude	Flywheel
Engine Type	IC Engine + turbo																			
	Gas Turbine																			
	Electric Motor																			
	Stirling																			
	Diesel																			
Conv. Efficiency	Fixed Pitch Prop																			
	Variable pitch Prop																			
	Jet																			
Fuel	Hydrocarbon																			
	H2 (liquid)																			
Power Option	Not Regen																			
	Renegerative																			
	Hybrid																			
Primary Power Source	Battery																			
	Fuel Cell																			
Energy Storage	Solar																			
	Beam																			
	altitude																			
	Flywheel																			

Figure 5.56: Incompatibility matrix of propulsion, fuel and power systems.

5.3.3 Step 3: Creation of the Decision Model

In Step 2 of the proposed methodology, relationships are identified between the various elements of the hierarchical model. The objective of this step is to establish a decision model by determining the strength of the relationships and the relative importance of the hierarchical components through pairwise comparisons. The creation of the decision model includes three activities as illustrated in Figure 5.57.

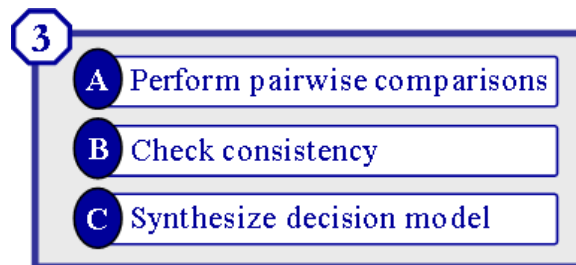


Figure 5.57: Step 3: Activities involved in the decision model.

The pairwise comparisons, activity (3-A), are performed sequentially for every cluster and not in bulk. For instance the first set of pairwise comparisons for the requirements mapping is between the scenario and the mission segments, as shown in Figure 5.58. Once this mapping

is performed the design team goes through the different sets of pairwise comparisons for each mission segment, and subsequently for each operational MoE.

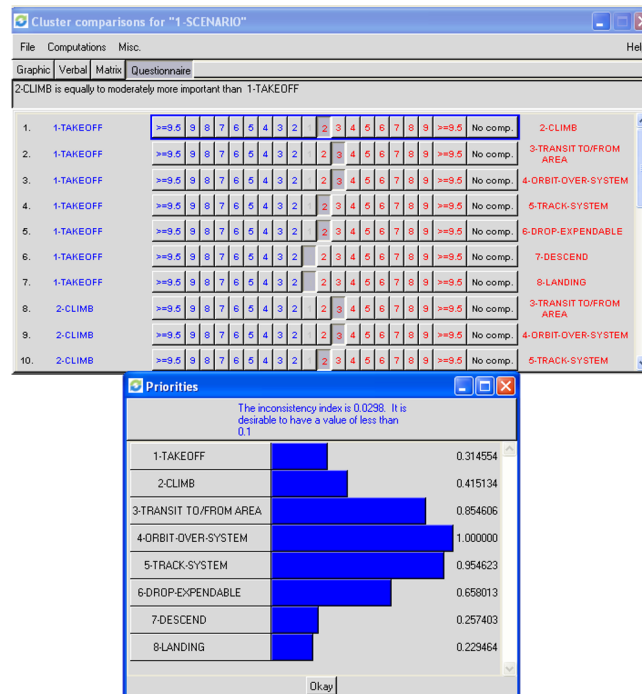


Figure 5.58: Pairwise comparisons to get the priorities of the mission segments.

For a given set of pairwise comparisons, once the preferences of the design team have been input to the decision model, it is possible to check the consistency of the comparisons, activity (3-B). As discussed in section 3.3.3, the inconsistency index can be calculated from the reciprocal and consistent properties of the comparison matrix. This feature is embedded in both the SuperDecisions software and the Excel based tool. If the consistency index is smaller than 0.1, the model is deemed consistent; if it is between 0.1 - 0.2 the model is acceptable; and if it is greater than 0.2, the model needs to be revisited to improve the consistency.

The results from Figure 5.58 show the inconsistency index being below 0.1 implying a consistent model. Also note that the most important mission segments represent the core of the hurricane tracker mission, which are orbit over the storm systems, track the hurricane, transit to the storm systems, and drop expendables into the hurricane. The relative priorities of the mission segments have a great impact on the decision model, because they influence

all the lower levels of the hierarchy.

The next set of pairwise comparisons involves the operational MoEs with respect to each mission segment, as illustrated in Figure 5.59. These priorities are obtained by answering the following question for each pairwise comparison: “*with respect to the success of the overall mission, within the “Climb” segment, which operational MoE is more important?*”

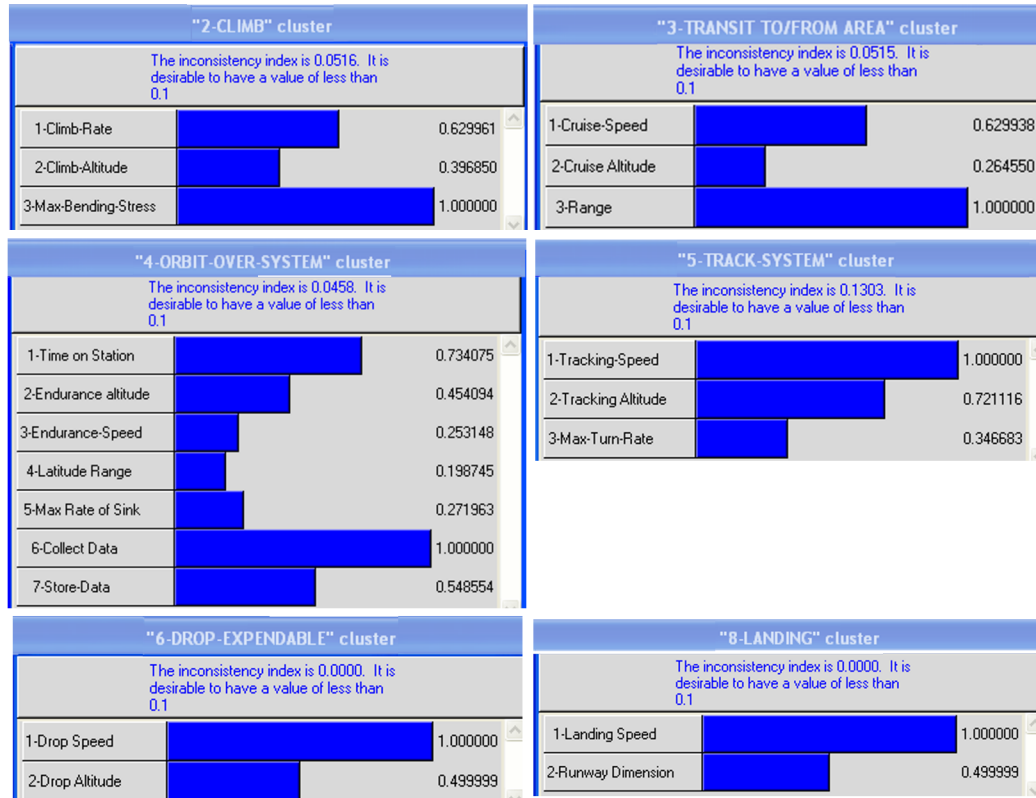


Figure 5.59: Operational MoEs priorities with respect to the mission scenario.

For mission segments including a unique operational MoE, no pairwise comparison can be performed and consequently the MoE priority is equal to 1. Figure 5.59 is depicting the “*ideal*” importance of the operational MoEs, implying that the priority vector has been normalized with an infinite norm, making the most important operational MoE equal to 1. Also note that the inconsistency index is provided for each of the mission segment.

Being able to check the consistency and visualize the priorities during the creation of the decision model is a great advantage of the proposed methodology. It encourages discussion between the team members, and challenges the team to think about specific aspects of the

problem, one at the time.

Assuming that the team is satisfied with the operational MoE priorities, the next step is to assess the systems and system MoE's relative importance. Each operational MoE is mapped differently to the systems and systems MoEs. That implies that different sets of pairwise comparisons need to be performed for each operational MoE. Figure 5.60 illustrates the sub-hierarchy (*subnet*) used for the operational “range” within the “transit” mission segment.

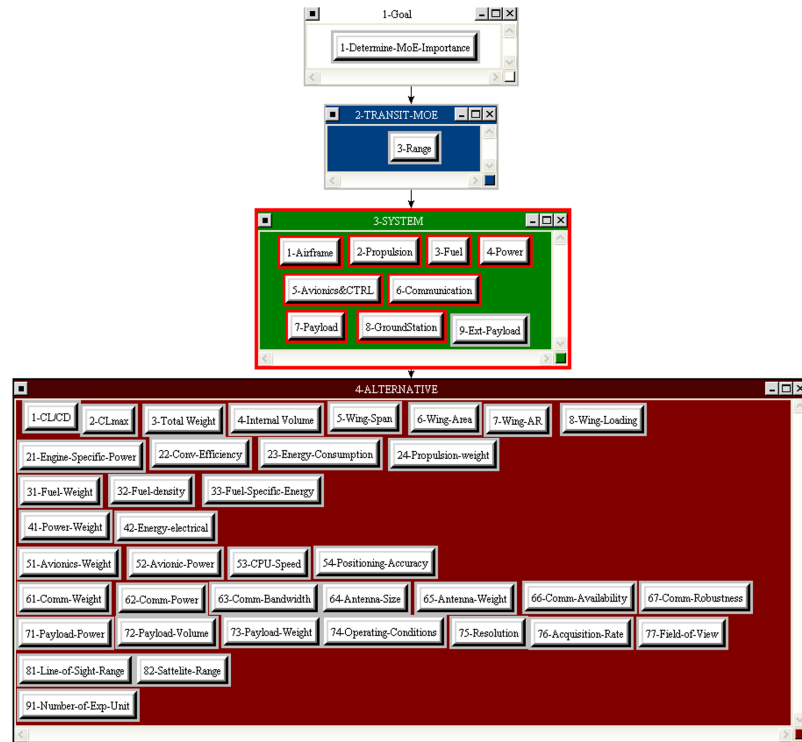


Figure 5.60: Example of sub-hierarchy used for the operational MoE.

The same structure of sub-hierarchy is used for all the operational MoEs. Each sub-hierarchy includes the operational MoE mapped with the systems, and the systems are mapped with their respective systems MoEs. Therefore, based on the specific operational relationships created in Step 2 of the proposed methodology, the design team performs all the pairwise comparisons, which result in the relative importance of the systems and the systems MoE for each operational MoE. Figure 5.61 presents the relative importance results of the systems and system MoEs.

		TAKEOFF			CLIMB			TRANSIT			ORBIT			TRACK			DROP			DESCEND & LAND																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
		1-Runway Dimension			1-Climb Rate			3-Max Banking Stress			2-Cruise Altitude			1-Cruise Speed			3-Range			1-Time on Station			2-Endurance Altitude			1-Endurance Speed			4-Latitude Range			5-Max Rate of Sink			6-Collect Data			1-Store Data			4-Tracking speed			3-Max Turn Rate			2-Drop altitude			1-Descent Rate			1-Landing Speed			2-Runway Dimensions																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
Aircraft	1-Airframe	1.00	0.50	0.69	1.00	0.63	0.46	0.31	0.49	1.00	0.00	0.47	0.49	0.44	0.68	0.75	0.41	0.21	0.24	0.35	0.44	1.00																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			

Figure 5.61: Results of the Systems and System MoEs pairwise comparisons.

For each set of pairwise comparisons, the consistency was checked and resulted in acceptable values. The results in Figure 5.61 represent the “*ideal*” priorities, and the most important systems and systems MoEs (value of 1) are highlighted in yellow. From these highlighted values, it is possible to identify the most important system and system MoE per operational MoE. From the results of the pairwise comparisons, it is possible to have more than one system or MoEs equal to 1. Also note that the priorities resulting from the systems MoEs in Figure 5.61 already take into account the importance of their respective system. This implies the synthesis of the system and system MoE levels of the hierarchy.

With the pairwise comparisons performed at every level of the hierarchy, the synthesis (bottom-up) process can start to create the ranking of the hierarchical model components (activity 3-C). Since there are specific systems MoEs for each system, the synthesis process differs slightly from the desirability formula described in section 3.5. The synthesis process is the same as the one explored in the Presidential helicopter experiment, which includes the following four steps:

1. Use the priorities from the pairwise comparison, note that the sum of the priorities per category is equal to 1;

2. Use the infinite norm so that the greatest value of the priority equals 1, these synthesized results are called “*ideal*” in SuperDecisions;
3. Multiple the ideal results with the priority of the higher level element (synthesis step);
4. Normalize the synthesis results with the L1-norm so that the sum of the elements of the level is equal to 1.

The only difference between the desirability equation (Eq. 3.12) and this synthesis process is the second step (infinite norm). This step is required to ensure that the number of alternatives per cluster does not bias the relative importance. These synthesis steps are illustrated in Figure 5.62, where the operational MoEs are synthesized with the priorities of the mission segments.

Mission Segment	Priority	OPS MoE	1	2	3	4
1-TAKEOFF	0.06716	1-Runway Dimension	1.00	1.00	0.07	0.032
2-CLIMB	0.08863	1-Climb Rate	0.31	0.63	0.06	0.027
		2-Climb Altitude	0.20	0.397	0.04	0.017
		3-Max Bending Stress	0.49	1	0.09	0.043
3-TRANSIT TO/FROM AREA	0.18246	1-Cruise Speed	0.30	0.55	0.10	0.048
		2-Cruise Altitude	0.16	0.303	0.06	0.027
		3-Range	0.54	1	0.18	0.088
4-ORBIT OVER SYSTEM	0.21350	1-Time on Station	0.21	0.734	0.16	0.075
		2-Endurance Altitude	0.13	0.454	0.10	0.047
		3-Endurance Speed	0.07	0.253	0.05	0.026
		4-Latitude Range	0.06	0.199	0.04	0.020
		5- Max Rate of Sink	0.08	0.272	0.06	0.028
		6-Collect Data	0.29	1	0.21	0.102
		7-Store-Data	0.16	0.549	0.12	0.056
5-TRACK SYSTEM	0.20381	1-Tracking speed	0.48	1	0.20	0.098
		2-Tracking Altitude	0.35	0.721	0.15	0.071
		3-Max Turn Rate	0.17	0.347	0.07	0.034
6-DROP EXPANDABLE	0.14049	1-Drop Speed	0.67	1	0.14	0.067
		2- Drop altitude	0.33	0.5	0.07	0.034
7-DESCEND	0.05496	1-Descend Rate	1.00	1.00	0.05	0.026
8-LANDING	0.04899	1-Landing Speed	0.67	1	0.05	0.024
		2-Runway-Dimension	0.33	0.5	0.02	0.012

Figure 5.62: Synthesis of the operational MoE with the mission segment.

As seen from Figure 5.62, the synthesis results (3) are normalized with the L1-norm (step 4) so that their sum is equal to 1. From the synthesis results of the hierarchical model, it is possible to create the rankings of the mission segments (Figure 5.63), the operational MoEs (Figure 5.64), the systems (Figure 5.65), and the systems MoEs (Figure 5.66).

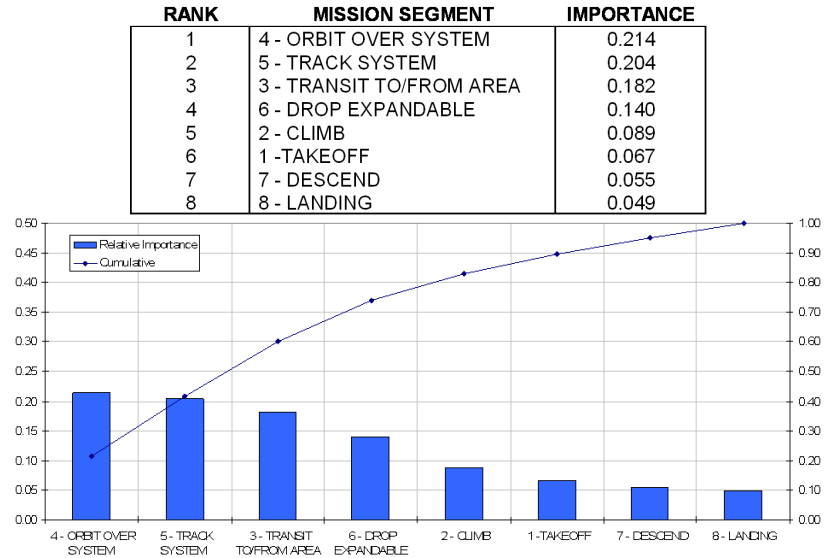


Figure 5.63: Ranking and relative importance of mission segment.

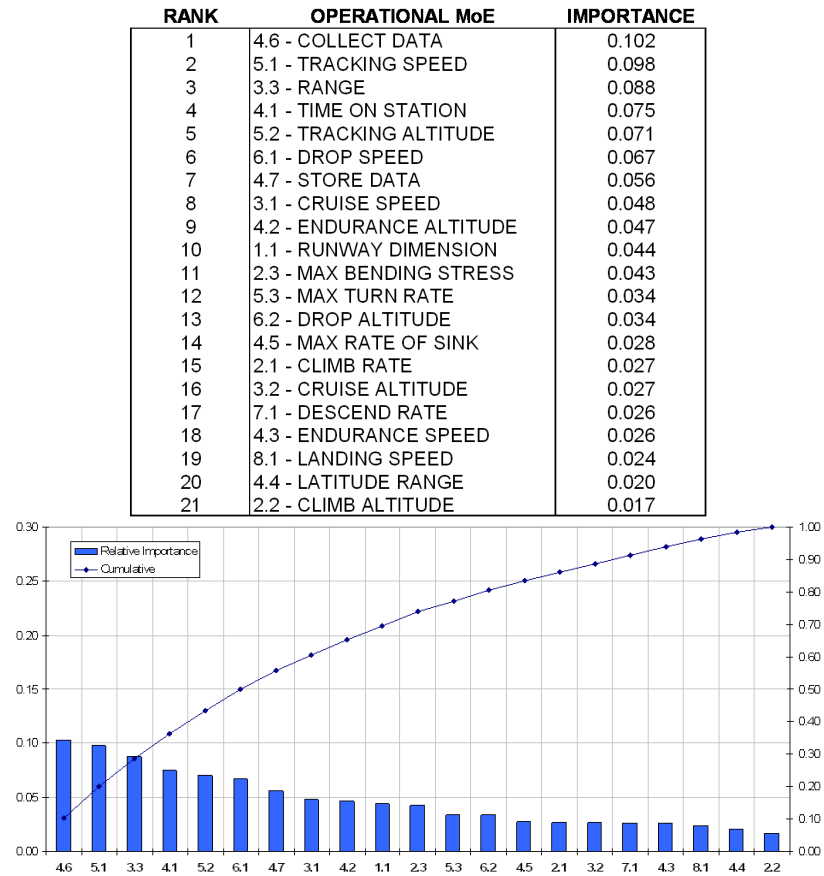


Figure 5.64: Ranking and relative importance of the operational MoE.

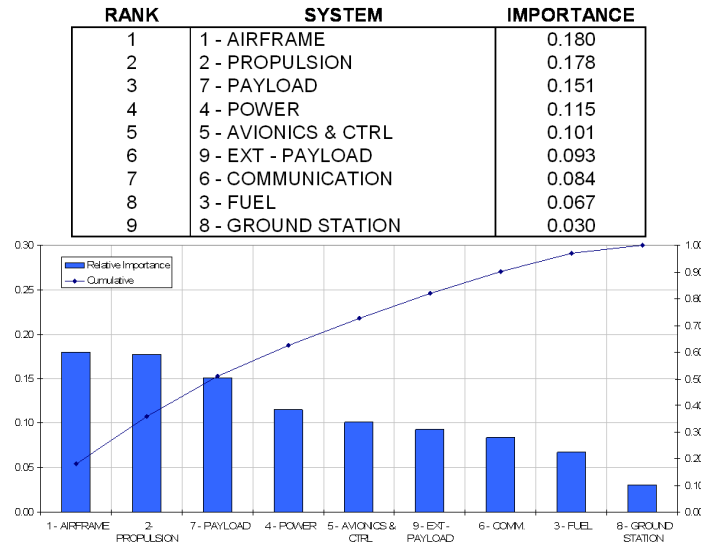


Figure 5.65: Ranking and relative importance of the systems.

In figures 5.64 & 5.66 the first digit of the operational and system MoE names represent the corresponding mission segment and system respectively. These final rankings represent the results of all the pairwise comparisons that were performed and synthesized in the creation of the decision model. Each of the rankings provides specific guidance to the design team by pointing toward a justified and logical starting point to the project.

The mission segment ranking provides a starting point to define the different level of success of the mission. The ranking of the operational MoEs takes into account the importance of the mission and establishes the most important operational tasks to achieve the mission. The system ranking indicates the most important systems that need to be considered to achieve the operational MoE. Finally, the ranking of the system MoEs takes into account all the previous levels, and establishes the most important system MoEs that need to be considered first in the morphological analysis. The mapping of the system alternatives and the decision model is defined in the next section.

At this point, one may wonder how the epistemic uncertainty surrounding the relative importance of the hierarchical elements affects these rankings. Can the results of these rankings robustly model the achievement of the mission? In order to provide more information to the decision makers regarding the variability of the rankings and consequently reducing

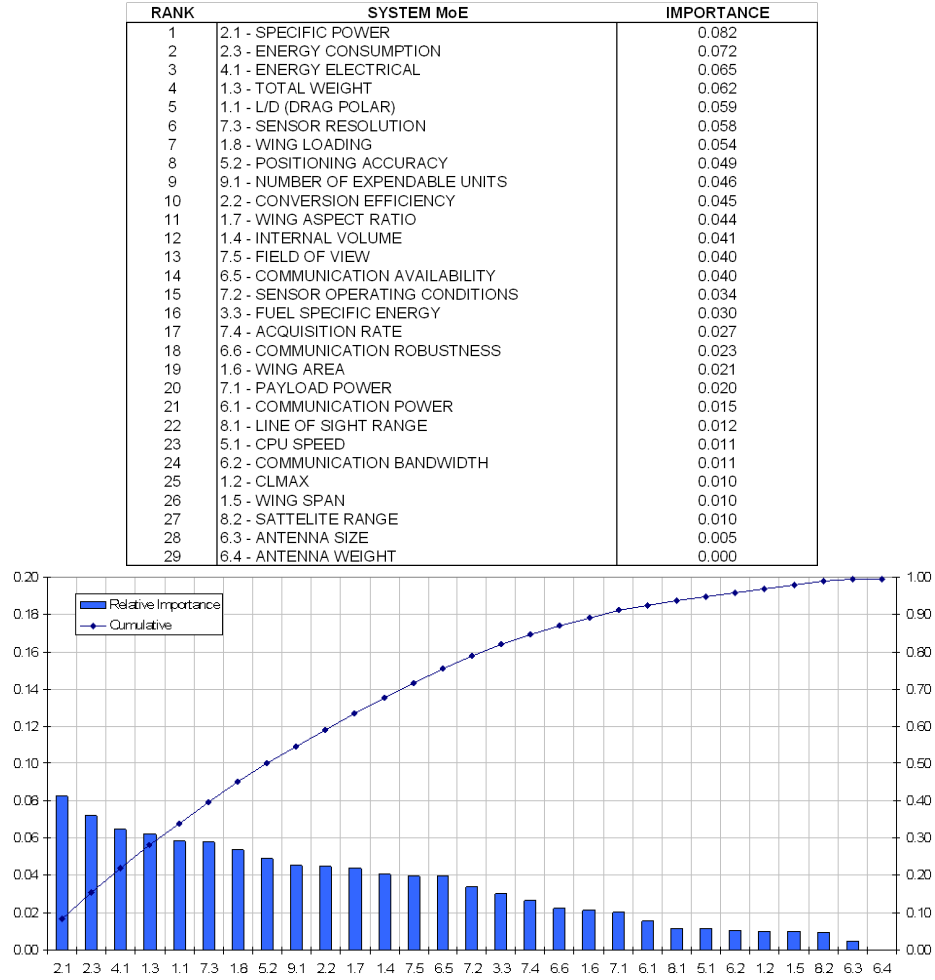


Figure 5.66: Ranking and relative importance of the systems MoEs.

the epistemic uncertainty, Monte Carlo methods are applied to the decision model in the next section.

5.3.4 Step 4 & 5: Assess the Uncertainty & Perform Benefits-Costs-Risks Analysis

This section discusses the application of the uncertainty analysis to the decision model. The first part describes how the propagation of the uncertainty in the model affects the rankings of the hierarchical components. The second part of this section discusses the mapping between the systems MoEs and the systems alternatives through a Benefits-Costs-Risks (BCR) model. The third and last part of this section describes the influence of the uncertainty propagation within the BCR model.

Figure 5.67 illustrates the specific activities involved in the uncertainty analysis (Step 4) and the BCR analysis (Step 5). These steps of the proposed methodology are intertwined because the uncertainty analysis is a critical element to establish the importance of the requirement (Step 5).

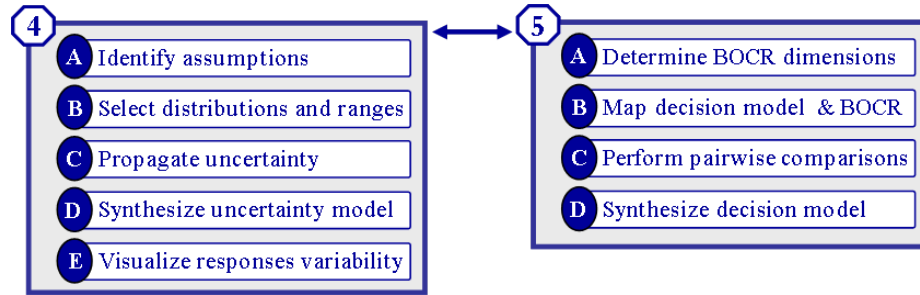


Figure 5.67: Step 4 & 5: Activities involve in the uncertainty and BCR analyses.

The first part of the uncertainty analysis is to assess how the propagation of the uncertainty in the decision model affects the ranking of the hierarchical components. The five activities of Step 4 are applied to determine the variability of the ranking. **Activity 4-A**, identify the major assumptions, often depends on the level of knowledge of the design team regarding specific areas of the hierarchical model. On one hand if the design team has more knowledge about the propulsion systems than the payload systems, then one can assume that the payload uncertainty will be higher. On the other hand if the design team is tackling a revolutionary system, implying a low level of knowledge, then a uniform distribution of uncertainty should be expected for the entire hierarchical system.

The **activity 4-B** of Step 4, select distributions and ranges, thus depends on the level of knowledge. Monte Carlo methods can be used with any type of random variable (input variable) distributions. For a low level of knowledge the uniform distribution is usually recommended, as the level of knowledge increases the design team can try using a triangular or normal distribution. In this experiment a low level of knowledge is assumed; Figure 5.68 shows the ranges of the operational MoEs considered for the uncertainty propagation using uniform distributions.

Using these ranges, the uncertainty is propagated to the model using the Monte Carlo algorithm presented in section 4.2.4 (Figure 4.17). This algorithm is required because the

	Actual Priority	Low (%)	High (%)	Minimum	Maximum
1.1 - Runway Dimension	1.000	0	0	1	1
2.1 - Climb Rate	0.311	40	40	0.186	0.435
2.2 - Climb Altitude	0.196	40	40	0.117	0.274
2.3 - Max Bending Stress	0.493	40	40	0.296	0.691
3.1 - Cruise Speed	0.297	40	40	0.178	0.416
3.2 - Cruise Altitude	0.163	40	40	0.098	0.229
3.3 - Range	0.540	40	40	0.324	0.755
4.1 - Time on Station	0.212	40	40	0.127	0.297
4.2 - Endurance Altitude	0.131	40	40	0.079	0.184
4.3 - Endurance Speed	0.073	40	40	0.044	0.102
4.4 - Latitude Range	0.057	40	40	0.034	0.080
4.5 - Max Rate of Sink	0.079	40	40	0.047	0.110
4.6 - Collect Data	0.289	40	40	0.173	0.405
4.7 - Store-Data	0.159	40	40	0.095	0.222
5.1 - Tracking speed	0.484	40	40	0.290	0.677
5.2 - Tracking Altitude	0.349	40	40	0.209	0.488
5.3 - Max Turn Rate	0.168	40	40	0.101	0.235
6.1 - Drop Speed	0.667	40	40	0.400	0.933
6.2 - Drop altitude	0.333	40	40	0.200	0.467
7.1 - Descend Rate	1.000	0	0	1.000	1.000
8.1 - Landing Speed	0.667	40	40	0.400	0.933
8.2 - Runway-Dimension	0.333	40	40	0.200	0.467

Figure 5.68: Operational MoE assumptions for uncertainty analysis.

sum of the priorities corresponding to every mission segment needs to be equaled to 1. For example in Figure 5.68 the sum of the “*cruise speed*”, “*cruise altitude*”, and “*range*” must be equaled to 1. The algorithm has been automated within the Excel based tool, the Visual Basic macro can be found in Appendix D.

The algorithm generates the random numbers for each random variable. These random values are then put into the decision model for the uncertainty propagation (**activity 4-C**). With these new priorities the decision model is synthesized as demonstrated in Figure 5.62. From these synthesis values (**activity 4-D**) correspond new operational MoE rankings that can be stored for each Monte Carlo simulation. Figure 5.69 illustrates the impact of the uncertainty analysis on the operational MoEs after 1000 Monte Carlo simulations.

In Figure 5.69 the “actual ranking” represents the ranking directly obtained from the decision model (without uncertainty). It is expected to have such a wide variation in ranking due to the large ranges included in the input distributions. Since the Monte Carlo results are stored, it is possible to filter the results and observe for each ranking the corresponding operational MoE values.

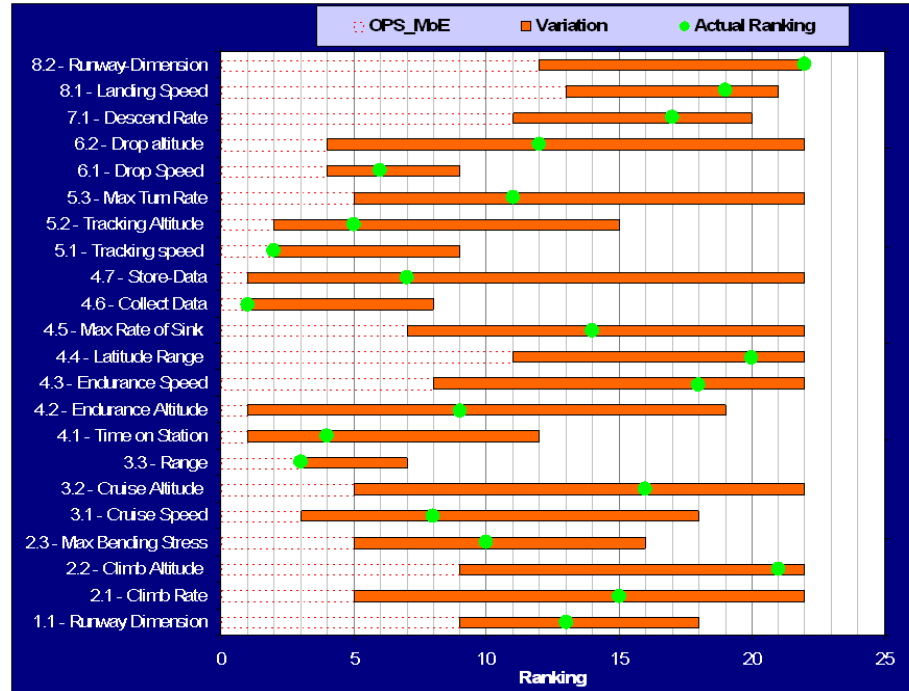


Figure 5.69: Operational MoEs Ranking variability from uncertainty analysis (1000 simulations).

The variation of the operational MoEs also has an impact on the lower levels of the decision hierarchy. Figure 5.70 illustrates the impact of the variation in operational MoEs on the system rankings.

From Figure 5.70, it can be seen that even though there are large variations in operational MoEs, the ranking of the systems is relatively stable. By observing the variation of the operational MoEs, it can be noticed that the most important operational MoEs remain significantly important even when taking into account the uncertainty. Through the systems, the uncertainty can also be propagated to the systems MoEs as illustrated in Figure 5.71.

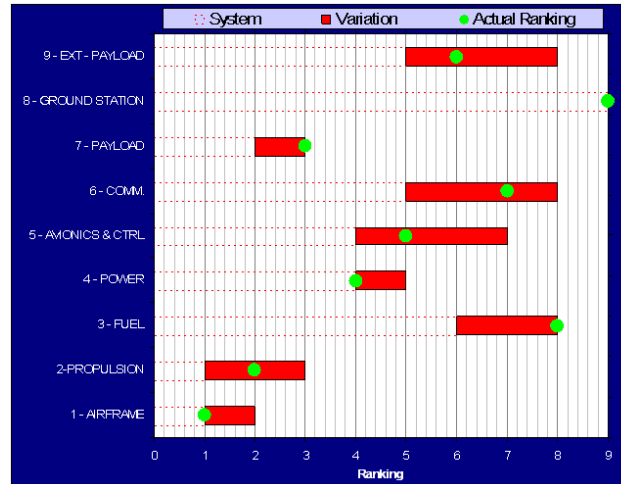


Figure 5.70: Systems ranking variability from uncertainty analysis.

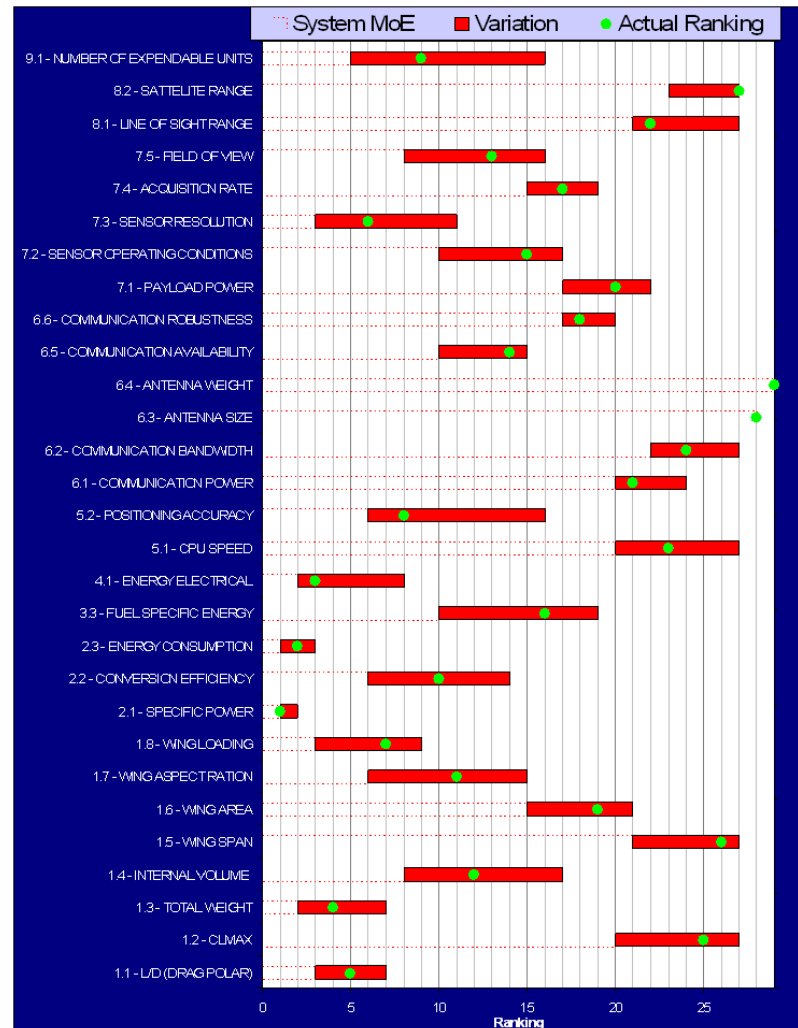


Figure 5.71: System MoEs ranking variability from uncertainty analysis.

From the ranking of systems MoEs, it can be observed that even if the airframe system is ranked first in Figure 5.70, the propulsion and power systems MoEs are the top ranked in Figure 5.71. These results can be explained by analyzing the hurricane tracking mission which requires a long range and long endurance from the vehicle. Since the airframe is constrained in volume for the fuel, then these requirements can only be achieved through highly efficient or regenerative propulsion and power systems. The next activity of this section is to map the systems MoEs with the systems alternatives.

5.3.4.1 Perform Benefits-Costs-Risks Analysis

The Step 5 of the proposed methodology consists of mapping the systems MoEs with the systems alternatives through a Benefits-Costs-Risks (BCR) model. The objective of this activity is to strengthen the decision model by taking advantage of available information that can be derived from existing alternatives. Ideally, all the systems MoEs should be mapped to systems alternatives, but the main objective of this experiment is to provide insights on the proposed methodology while answering the research questions, consequently a subset of the systems MoEs will be used in the BCR model.

The systems MoEs considered are related to the propulsion, power and fuel systems, which include the three most important MoEs. The matrix of alternatives used was illustrated in Figure 5.55, and is reproduced here for clarity:

SYSTEM	SYSTEM MoE	ALTERNATIVE				
PROPULSION		1	2	3	4	5
Engine Type	Specific Energy & Energy consumption	IC Engine + turbo	Gas Turbine	Electric Motor	Stirling	Diesel
Conversion Type	Conversion Efficiency	Fixed Pitch Prop	Variable pitch Prop	Jet		
FUEL						
Fuel Type	Fuel Specific Energy	Hydrocarbon	H2 (liquid)			
POWER						
Power option	Power specific energy	Not Regen	Renenerative	Hybrid		
Primary energy storage		Battery	Fuel Cell			
Secondary energy storage		Solar	Beam	altitude	Flywheel	

The objective of using the matrix of alternatives with the BCR analysis is to quickly go through all the compatible combinations of alternatives and compare them in order to establish threshold values for the systems MoEs. Note that in this section the main source of quantitative information for the systems alternatives is taken from a NASA technical report entitled “*High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development*” [135]. This report includes specific performance, costs and risks information for the systems alternatives considered.

The first activity of this step is to determine the criteria involved in the Benefits-Costs-Risks hierarchies (**activity 5-A**). For this experiment, the Benefits hierarchy is defined in terms of performance where larger benefit implies better performance. The system alternatives are then compared with respect to the system MoEs, having the “best” alternative resulting in a normalized benefit of 1. The normalized benefits values will be synthesized with the decision model in **activity 5-D**.

The costs hierarchy for the system alternatives is divided into three cost categories: development, manufacturing and operating costs. For each cost category the systems are compared in the mind set that a larger relative importance implies a more expensive system. The normalized cost values can be transferred into monetary values if some of the systems alternatives costs are available. Note that for the Costs hierarchy, the importance of the system MoEs does not influence the specific cost of an alternative, therefore the Costs hierarchy can be considered independently from the decision model.

The Risks hierarchy also includes three criteria: system complexity, growth factor (mass) and safety. As for the cost, the system alternatives are compared with the mindset that a higher relative importance implies a greater risk. For this hierarchy, the riskiest alternative per system MoE corresponds to a normalized risk of 1. The normalized risk values are then mapped with the decision model, assuming that an important system MoE with a high risk value represents a bigger risk than a less important system MoE with the same normalized risk value. This mapping between the normalized risk values and the decision model will be discussed in **activity 5-D** of this section.

The next activity is to map the systems MoEs with the Benefits-Costs-Risks hierarchies (**activity 5-B**). This section first describes the UAV Benefits model followed by the Costs and Risks models. From Reference [135], quantitative information is available for the propulsion specific power and energy consumption MoEs corresponding to the five engine types included in the matrix of alternatives. Table 5.8 lists both the actual and normalized values for these two system MoEs. It is to be noted that the values of specific power and specific energy consumption may vary as a function of power setting and altitude respectively.

From this table it can be noticed that the preferred MoE direction (i.e., maximize or

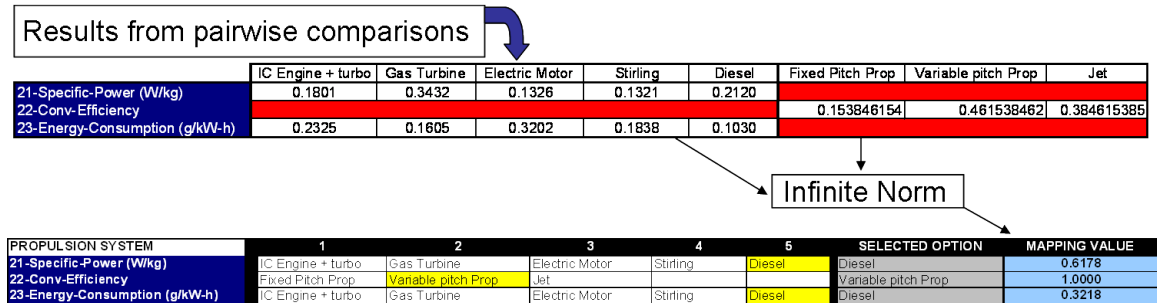
Table 5.8: Benefits mapping: Specific power and energy consumption [135].

Alternative	Specific Power (W/kg) (*)	Energy Consumption (g/(kW-h)) (**)	Specific Power (Normalized)	Energy Consumption (Normalized)
LH ₂ IC Engine + Turbo	222 (0.5 to 1)	80 (0 to 21 km)	0.180	0.231
LH ₂ Gas Turbine	425 (0.5 to 1)	116 (0 to 21 km)	0.344	0.160
Electric Motor	164 (0.3 to 1)	57 (0 to 21 km)	0.133	0.325
LH ₂ Stirling Engine	162 (0.5 to 1)	101 (21 km)	0.131	0.183
Diesel Engine	263 (0.5 to 1)	182.5 (0 to 21 km)	0.213	0.101

(*) Fraction of rated sea level power

(**) Vehicle altitude range of specific fuel consumption

minimize) is taken into account in the normalized benefit values, where the highest benefits correspond to the highest specific power and lowest specific fuel consumption. For the conversion efficiency MoE, no quantitative information is used, and consequently the normalized benefits are resulting from the pairwise comparisons priorities. Figure 5.72 shows how the normalized benefit values are represented in the Excel based tool.

**Figure 5.72:** Propulsion system MoEs benefits mapping.

The mapping values of Figure 5.72 are used for the mapping between the normalized benefit value and decision model priorities. The infinite norm is applied to assure that the alternative providing the highest benefit per MoE has a normalized value of 1. These values are then mapped with the relative importance of the respective systems MoEs, to determine their importance within the concept of operation.

The other system MoE considered in the benefit mapping is the power (electrical) specific energy. As with conversion efficiency, no quantitative information is used, instead the benefits model is established based on pairwise comparisons of the power options, and the primary and secondary sources of energy. Since multiple options are associated to a single

MoE, the mapping process is divided into four steps, as shown in Figure 5.73. The objective of this process is to establish a benefit value for all the different combinations of options.

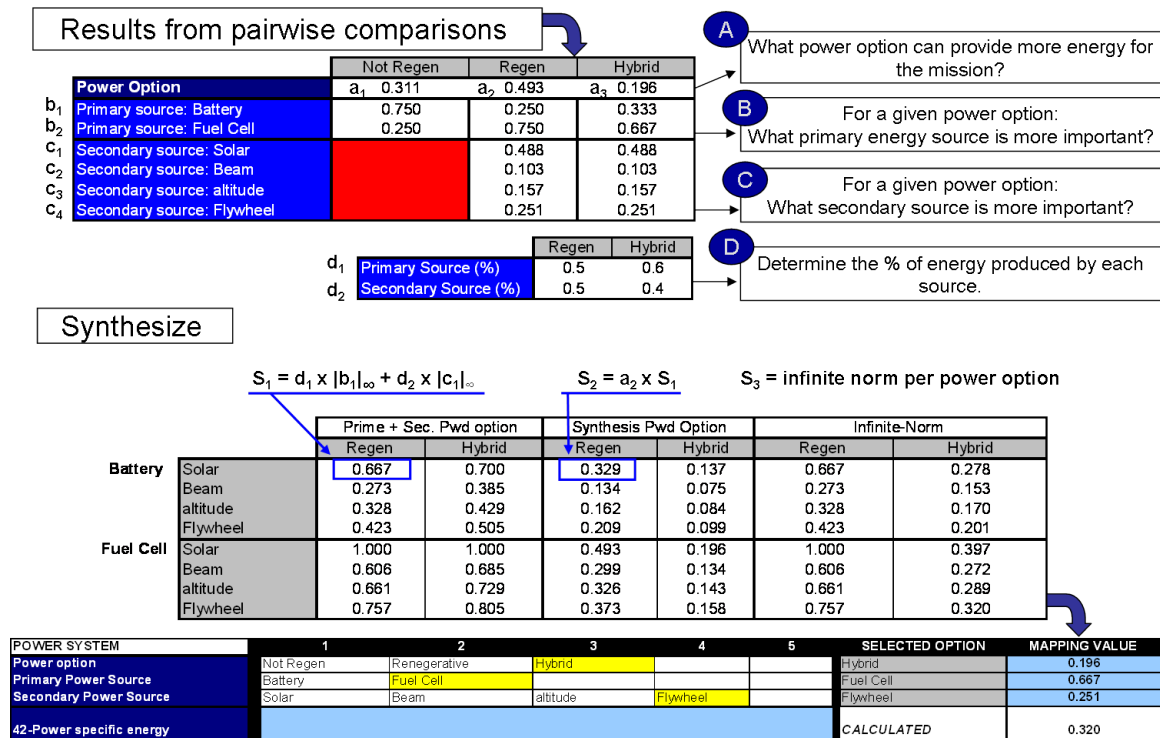


Figure 5.73: Power system MoE benefits mapping.

For this mapping the design team first establishes which option from *not regenerative*, *regenerative* and *hybrid* systems can provide enough power to achieve the mission (A). Subsequently, for each power option the team can estimate which alternatives best provide the required power (B & C). To combine the different power sources benefits (D), the team needs to estimate the percentage of energy that would be generated from each energy source. This synthesis process of the power sources is almost identical to the decision model synthesis process except that no L1-normalization is performed. From Figure 5.73, it can be observed that the combination of the fuel cell and solar panels provides the highest normalized benefit of 1.

The second mapping discussed in this section refers to the cost of the systems alternatives. The Costs model includes three criteria for the pairwise comparisons: development, manufacturing and operating costs. The development costs include all the non-recurring

costs like non-recurring engineering hours, tooling, infrastructure, and flight test. The manufacturing costs include all the recurring costs not related to the operations like recurring engineering hours, manufacturing labor hours, and material costs. For the last criteria, the operating costs are present throughout the operational life of the vehicle and generally include the operating labor hours, maintenance costs, consumables, and operating facility costs.

The synthesis of the costs pairwise comparisons results in normalized values that can be mapped to monetary figures when available. Table 5.9 lists the costs of three alternatives, one per system MoE, that will be used as reference to estimate the costs of the other alternatives. It is to be noted that these cost values correspond to an average between commercial-of-the-shelf hardware values (lowest costs) and unique hardware applications (highest costs) [135].

Table 5.9: Cost Mapping: Quantitative information [135].

System MoE	Alternative	Cost (\$k) FY2006
Specific power & Energy consumption	LH ₂ IC engine	50
Conversion efficiency	Fixed pitch propeller	15
Power specific energy	PEM fuel cell*	1,669

* Include turbochargers and radiators

Before integrating these monetary values to the cost model, the design team has to perform two sets of pairwise comparisons as shown in Figure 5.74. The first set of pairwise comparisons defines the relative importance of the cost categories within the Life Cycle Cost (LCC) of the system, while the second set of pairwise comparisons establishes the relative costs of the different systems alternatives for each category.

The synthesis of the relative costs for each alternative is calculated with a weighted sum (“*Total*” column) and an infinite norm (“*Synthesis*” column). The synthesis results can then be combined with the monetary values of Table 5.9 to estimate the costs of the other alternatives. Note that if monetary values are available for all the alternatives, there is no need to perform the pairwise comparisons and the monetary costs can be directly mapped with the alternatives.

For the power system, the cost model needs to take into account the combination of

(1) - In term of Life Cycle Costs, which category is more important?

Development	0.3
Manufacturing	0.3
Operation	0.4

(2) - Pairwise comparisons: For each category, which alternatives cost more?

e.g.: *IC Engine* = $(0.0179 \times 0.3) + (0.0261 \times 0.3) + (0.0258 \times 0.4) = 0.0235$

	Development	Manufacturing	Operation	Total	Synthesis	Total (\$k)
IC Engine + turbo	0.0179	0.0261	0.0258	0.0235	0.0264	50.00
Gas Turbine	0.8901	0.8815	0.8941	0.8891	1.0000	1890.96
Electric Motor	0.0283	0.0175	0.0194	0.0215	0.0242	45.76
Stirling	0.0463	0.0493	0.0422	0.0455	0.0512	96.87
Diesel	0.0174	0.0255	0.0186	0.0203	0.0228	43.20
Fixed Pitch Prop	0.163	0.163	0.163	0.1634	0.3029	15.00
Variable pitch Prop	0.297	0.297	0.297	0.2970	0.5503	27.26
Jet	0.540	0.540	0.540	0.5396	1.0000	49.53

(3) – Use relative importance and quantitative value to estimate costs

Assumed Costs	(k\$)
IC Engine + turbo	50
Fixed Pitch Prop	15
PEM Fuel Cell	1669

Electric Motor cost = $(0.0242 / 0.0264) \times 50 = 45.76$

Figure 5.74: Propulsion system MoE costs mapping.

the primary and secondary power sources. The synthesis process includes the same four steps as for the benefit model, except that the pairwise comparisons are performed in terms of development, manufacturing and operation costs. Figure 5.75 illustrates the four steps associated with the cost model of the power specific energy MoE.

Step D of Figure 5.75 is required to define how the cost is distributed between the primary and secondary power source. The last step of the synthesis process is to map the normalized costs with monetary values. In order to do that, the fuel cell cost, listed in Table 5.9, is mapped to the normalized cost of *0.8062*, since the fuel cell costs does not include any secondary power source. Using this normalized value as reference, all the other power system costs can be inferred as demonstrated for the propulsion MoE costs (Figure 5.74). Also it is to be noted that the pairwise comparisons are based on the assumption that a fixed value of total power is required to complete the mission. This assumption implies that to perform the same mission, a non-regenerative fuel cell system would need to carry more fuel than a regenerative fuel cell system. This specific operational aspect is taken into account within the operating cost comparisons.

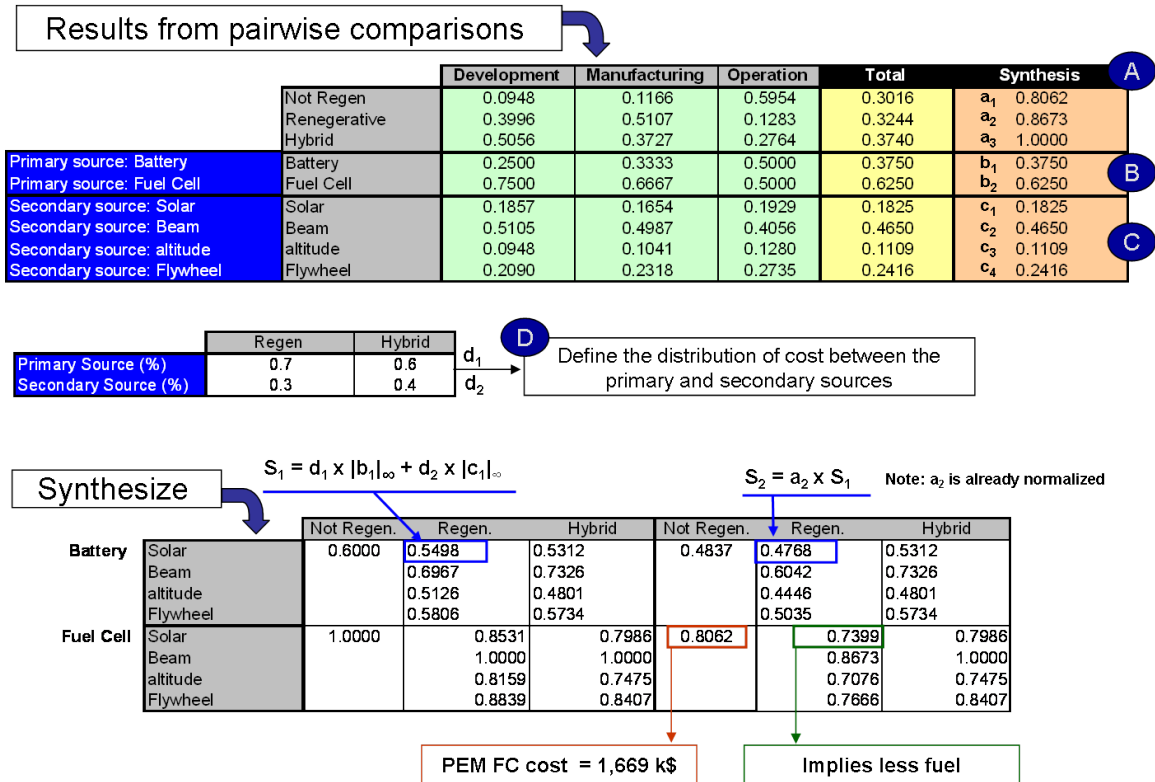


Figure 5.75: Power system MoE costs mapping.

The last mapping of the BCR model requires the estimation of the risks related to the system alternatives. The risk model includes three criteria for the pairwise comparisons: system complexity, growth factor and safety. The system complexity criteria evaluate the risks associated with the use of new technologies that are not currently mature and the integration of these new technologies to the vehicle. The growth factor includes the risks associated with the mass growth of the systems during their development [135]. The final risk criterion correspond to the vehicle safety, which refers to the risks associated with the handling of the vehicle on the ground, fuel handling, and safety of the vehicle while flying its mission. As the design team is performing the pairwise comparison, it is important that the alternatives are compared so that the safest alternative has the smallest normalized risk while the less safe alternative has a normalized risk of 1.

Figure 5.76 illustrates the mapping of the systems alternatives in terms of the three risk criteria. Note that the total risk associated with the alternatives correspond to normalized values varying from 0 (no risk) to 1 (riskiest alternative).

(1) - In term of risk, which category is more critical?

Complexity	0.310
Growth Factor	0.493
Less Safety	0.196

(2) - Pairwise comparisons: For each category, which alternative is riskier?

	Complexity	Growth Factor	less Safety	Total	Synthesis	Total Risk
IC Engine + turbo	0.0980	0.1367	0.1691	0.1309	0.2899	0.2212
Gas Turbine	0.6309	0.3984	0.3044	0.4517	1.0000	0.7631
Electric Motor	0.0553	0.0884	0.1133	0.0829	0.1836	0.1401
Stirling	0.1711	0.2908	0.2743	0.2502	0.5539	0.4227
Diesel	0.0447	0.0856	0.1389	0.0833	0.1844	0.1407
Fixed Pitch Prop	0.1322	0.1518	0.4000	0.1942	0.4358	0.1269
Variable pitch Prop	0.3647	0.3401	0.4000	0.3591	0.8059	0.2347
Jet	0.5031	0.5081	0.2000	0.4456	1.0000	0.2912

(3) – For the success of the project, which system represents a bigger risk?

Engine Alternative	0.371
Conv-Efficiency	0.142
Power Systems	0.487

$$\text{Electric Motor Risk} = 0.1836 \times (0.371 / 0.487) = 0.1401$$

Figure 5.76: Propulsion system MoE risk mapping.

From the assessment of the risk model, it can be observed that the growth factor is considered to be riskier than the complexity and safety criteria. This assertion can be justified by assuming that if the mass of the vehicle increases, it will have a negative impact on the performance of other systems, and consequently reduce the effectiveness of the vehicle to perform its mission. Another important aspect of the mapping model is to consider the overall risk of the systems. Since the values in the “Synthesis” column are normalized to 1 for each category of systems, the third step of Figure 5.76 estimates the risks associated to a system unable to meet its respective MoEs. In other words, this step evaluates the risk on the project success if a system fails to meet its requirements. The total risk of the system alternatives is then obtained by combining the normalized risks from the three criteria of the risk model.

As for the Benefits and Costs models, the Risks model for the power systems is obtained by combining the primary and secondary power sources alternatives. Figure 5.77 illustrates the four step process used to synthesize the normalized risk of the different combinations of power alternatives.

In Figure 5.77, step D is used to emphasize that more risks are associated with the primary power source due to its consequence on the achievement of the mission. From the

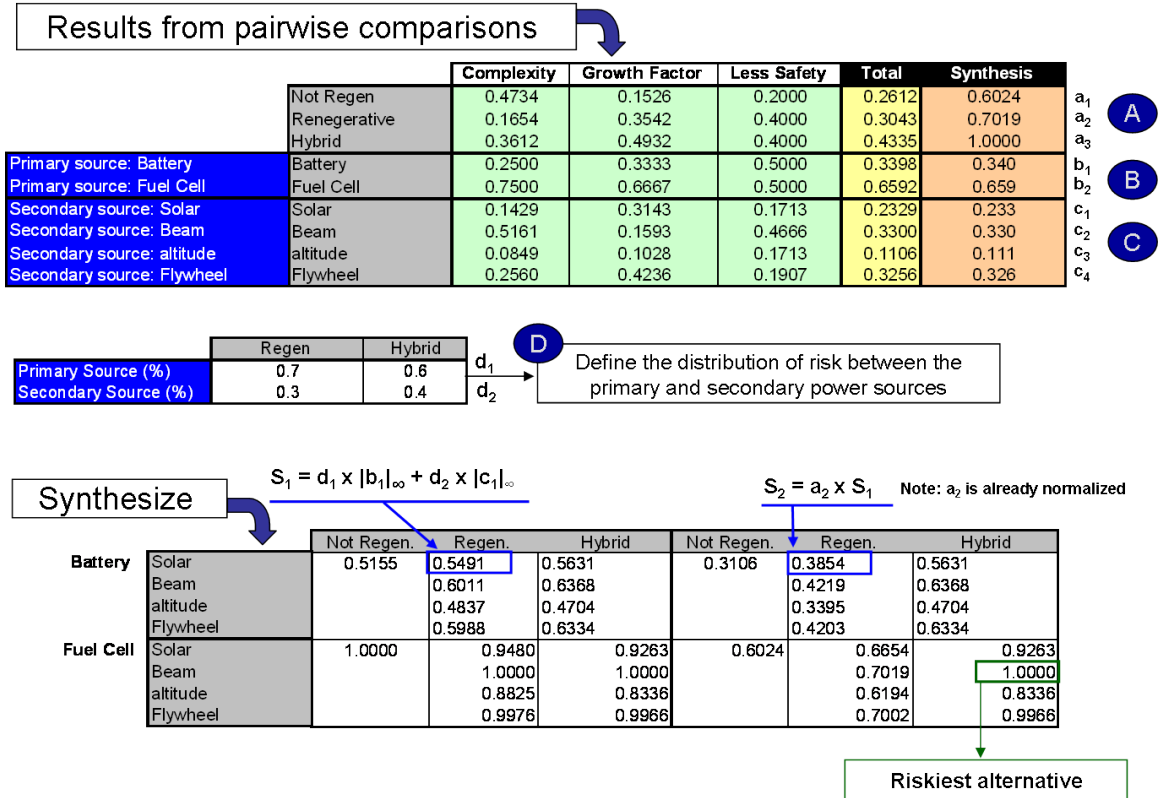


Figure 5.77: Power system MoE risk mapping.

same figure it can be observed that the combination of the fuel cell with the beam energy as secondary system is considered to be the riskiest alternative.

The last activity of Step 5 of the proposed methodology is to synthesize the results of the BCR model with the decision model (**activity 5-D**). As mentioned earlier in this section, only the systems alternatives Benefits and Risks are dependent on the relative importance of the system MoEs. In other words, the benefits and risks related to the most important MoE (*Specific Power*) are assumed to have a greater influence on the achievement of the mission than the benefits and risks of the least important MoE (*Antenna Weight*). As for the alternative costs, they are assumed to be independent from the relative importance of the system MoEs, and only depends on its development, manufacturing and operating costs.

In this experiment only the propulsion and power MoEs are mapped with specific system alternatives. The combined importance of these four MoEs represents around 27% of the overall importance of all the system MoEs. Table 5.10 lists the four system MoEs with their respective priority and ranking used for the BCR model.

Table 5.10: System MoE used in BCR mapping.

System MoE	Priority	Rank	Normalized Priority (\bar{w})
2.1 Specific Power	0.0830	1	0.3127
2.2 Conversion Efficiency	0.0451	10	0.1697
2.3 Specif Energy Consumption	0.0724	2	0.2729
4.1 Power Specific Energy	0.0650	3	0.2447

The normalized priority of Table 5.10 is used for the mapping between the system MoEs and the system alternatives to provide a greater contrast in the Benefits and Risks values. Therefore, the “ideal” combination of alternatives can theoretically correspond to a overall benefit of 1. Using these normalized priorities, the synthesized benefits and risks are calculated as follows:

$$\begin{aligned}
\textit{Synthesized Benefits} = & \quad \bar{w}_{2.1}\textit{Benefit}_{2.1} + \bar{w}_{2.2}\textit{Benefit}_{2.2} + \bar{w}_{2.3}\textit{Benefit}_{2.3} \\
& + \bar{w}_{4.1}\textit{Benefit}_{4.1} \\
\textit{Synthesized Risks} = & \quad \textit{Risk}_{Engine\ Type} (\bar{w}_{2.1} + \bar{w}_{2.3}) + \bar{w}_{2.2}\textit{Risk}_{2.2} + \bar{w}_{4.1}\textit{Risk}_{4.1}
\end{aligned} \tag{5.4}$$

In Eq. 5.4, it can be noticed that the engine type risk is associated with both the specific power and specific energy consumption MoEs. This risk synthesis thus tends to emphasize the importance of a low risk engine type for the integration with the vehicle. The synthesized costs values are simply obtained by adding the cost of each alternative.

Using Eq. 5.4, the next activity is to cycle through the matrix of alternatives and calculate the synthesized Benefits, Costs and Risks for all the compatible alternatives. This task is performed in the Excel tool using a Visual Basic macro to check the compatibility of the alternatives, while storing the Benefits, Costs and Risks values. This macro can be found in Appendix D.

With the incompatibility matrix of Figure 5.56, the macro goes through 138 compatible alternatives that are represented with a scatterplot matrix of Figure 5.78.

The points within the scatterplot matrix are regrouped by engine type. The main diagonal of the matrix represents the distribution of the synthesized Benefits, Costs and Risks.

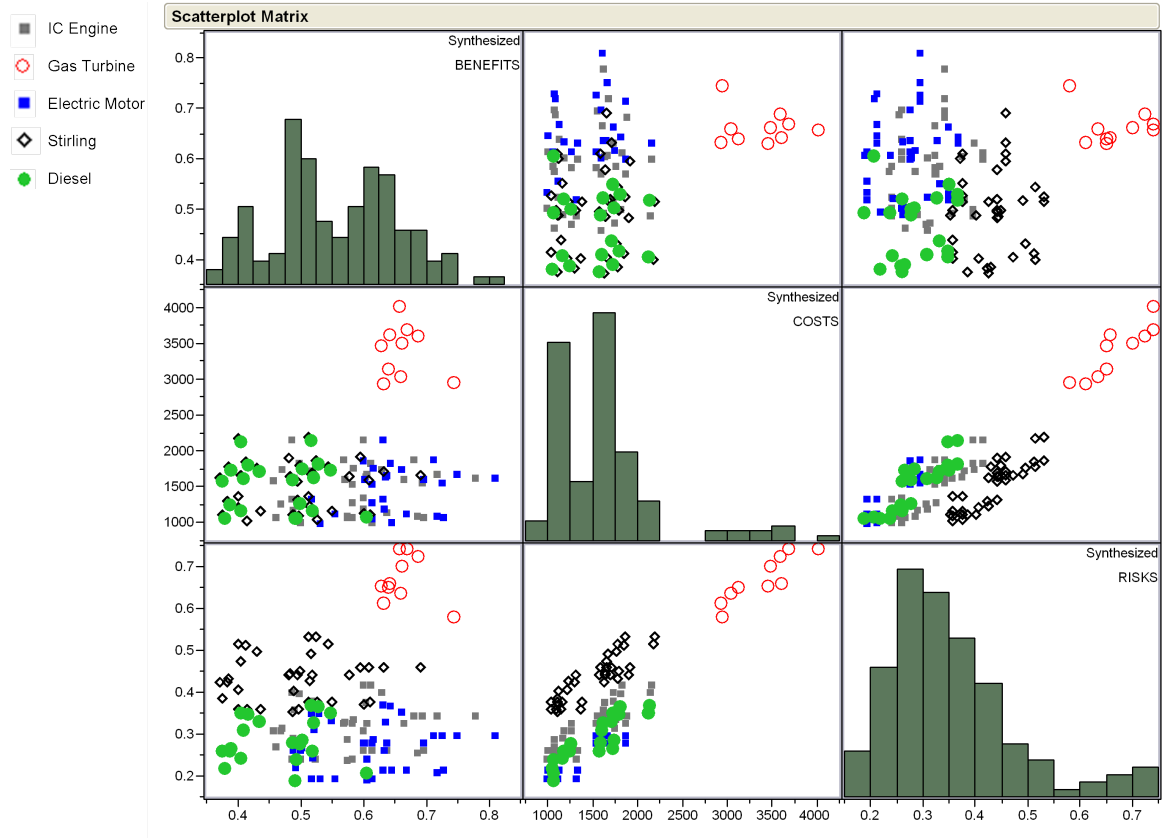


Figure 5.78: Synthesized values of the Benefits, Costs and Risks.

These distributions are useful to provide a quick overview of how the BCR spaces are populated.

From Figure 5.78 it can be observed that the most promising alternatives are the ones including (1) electric motors, followed by IC engine (2), and diesel engines (3). Even though the gas turbine and Stirling engines have the potential of providing great benefits, the gas turbine engine is more expensive and riskier, whereas the Stirling engine is simply considered riskier than the other three types of engines.

From this analysis, the most promising configuration of alternative with a normalized benefits of 0.81 combines electric motors with variable pitch propellers, and a regenerative power system combining the PEM fuel cell and the solar panels.

Using the BCR information gathered in this section, the final activity of Step 5 consists of performing an uncertainty analysis through the system MoEs and alternatives mapping.

5.3.4.2 Uncertainty Applied to the BCR Model

This section propagates the uncertainty through the Benefits-Costs-Risks mapping. The first objective is to determine the influence of the weighting attributed to the benefit, cost and risk criteria. For instance, if the stakeholders are under a small budget, then more importance needs to be attributed to the cost criterion. The second objective of this section is to determine the impact of the operational uncertainty of the BCR model. For a selected number of configurations, this analysis will be used to identify which alternatives are more robust to the variation of importance of the operational MoEs.

The first part of this section describes how the normalized benefits, costs and risks values obtained in the previous section are synthesized using the additive (negative) equation described in section 3.5.2. Recall that the additive (negative) equation has the following form (Eq. 3.16):

$$\text{Additive (negative)} : w_b \times B_p + w_o \times O_p - w_c \times C_p - w_r \times R_p$$

Where the (w) represents the weighting of the criteria, and B_p , C_p , and R_p correspond to the normalized benefits, costs, and risks respectively. The values calculated from this equation are called in this section, synthesized BCR value. Note that the normalized cost values can be obtained by normalizing by the greatest monetary value; so that the most expensive configuration has a normalized cost of 1.

The objective is to determine the influence of the weighting on the system alternatives. First, the number of alternatives can be reduced based on the results obtained in the previous section. All the gas turbine and Stirling engine configurations can be eliminated because of their combination of high risks and costs. That leaves 92 configurations, which is a large number to handle during the uncertainty analysis.

To further reduce the number of configurations, the synthesized BCR value is calculated for the 92 configurations assuming an equal weighting of the benefit ($w_b = 0.33$), cost ($w_c = 0.33$) and risk ($w_r = 0.33$) criteria. The 92 synthesized BCR values are illustrated in the contour plot of figures 5.79 and 5.80. The axes of these contour plots represent

the synthesized Benefits, and Risks obtained from Eq. 5.4, while the synthesized Costs are obtained by normalizing all the monetary values with the most expensive configuration found within the remaining 92 configurations.

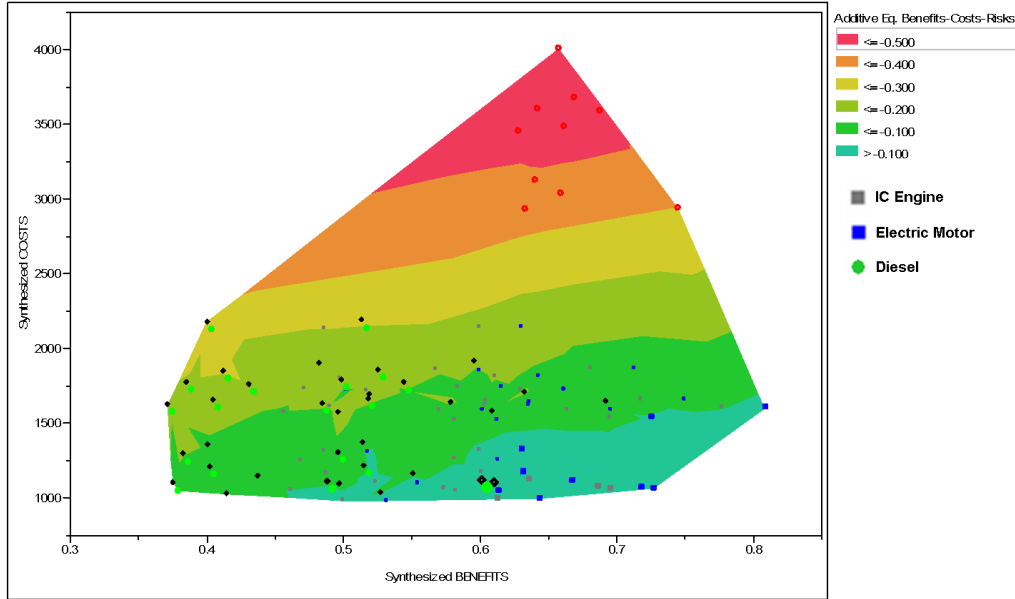


Figure 5.79: Contours of the synthesized BCR values as a function of the normalized Benefits and Costs.

The best configurations in terms of the synthesized BCR are located at the bottom right corner of the contour plots, maximizing the benefits and minimizing the costs and risks. Each data point of the contour plots corresponds to a specific configuration of systems alternatives. Therefore, the number of configurations is reduced by selecting the data points having a synthesized benefit greater than 0.6, a synthesized risk smaller than 0.3, a synthesized cost smaller than \$1,500k and a synthesized BCR value greater than -0.1. The configurations meeting all these criteria are listed in Table 5.11.

Table 5.11: Selected configurations from BCR analysis.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. PWD Source	Sec. PWD Source	Synthesized BCR Value
19	IC Engine + turbo	Variable pitch prop.	Not Regen	Battery		-0.0228
21	IC Engine + turbo	Variable pitch prop.	Renegerative	Battery	Solar	-0.0193
25	IC Engine + turbo	Variable pitch prop.	Renegerative	Fuel Cell	Solar	-0.1035
65	Electric Motor	Variable pitch prop.	Not Regen	Battery		0.0039
67	Electric Motor	Variable pitch prop.	Renegerative	Battery	Solar	0.0074
69	Electric Motor	Variable pitch prop.	Renegerative	Battery	altitude	-0.0097
71	Electric Motor	Variable pitch prop.	Renegerative	Fuel Cell	Solar	-0.0768
75	Electric Motor	Variable pitch prop.	Hybrid	Battery	Solar	-0.0575
129	Diesel	Variable pitch prop.	Not Regen	Battery		-0.0330

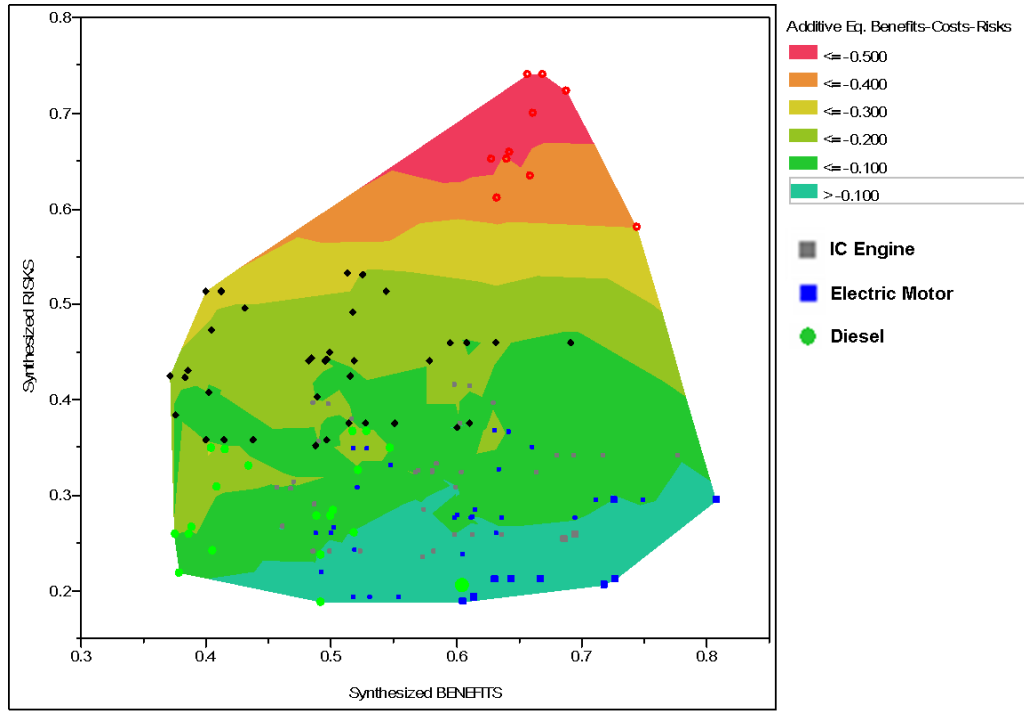


Figure 5.80: Contours of the synthesized BCR model as a function of the normalized Benefits and Risks.

The configurations listed in Table 5.11 are then used to analyze the uncertainty surrounding the benefits, costs and risk weighting. Table 5.12 presents a weighting scenario considered to perform the Monte Carlo simulations. Note that uniform distributions are used for the three criteria.

Table 5.12: BCR weighting scenario.

Criterion weight	Min Value	Max Value
Benefit	0.3	0.5
Cost	0.3	0.6
Risk	0.2	0.5

Ideally the creation of the weighting scenario would involve the stakeholders and the design team. The weighting scenario of Table 5.12 implies that every criterion has the potential of dominating the other two. The objective of propagating this uncertainty through the decision model is to evaluate, under this specific weighting scenario, the configuration probability of having a positive synthesized BCR values. In other words, based on this range of weighting criteria, what is the probability that the configuration benefits will be greater

than both the associated costs and risks of this configuration?

To answer this question, uniform distributions are first applied to the benefit, cost and risk weighting, and 10,000 Monte Carlo simulations are performed. From the stored results of the Monte Carlo simulations, the Probability Density Function (PDF) of the input criteria can be visualized to verify how well they follow the desired uniform distributions. Figure 5.81 shows the resulting PDF of the weighting criteria.

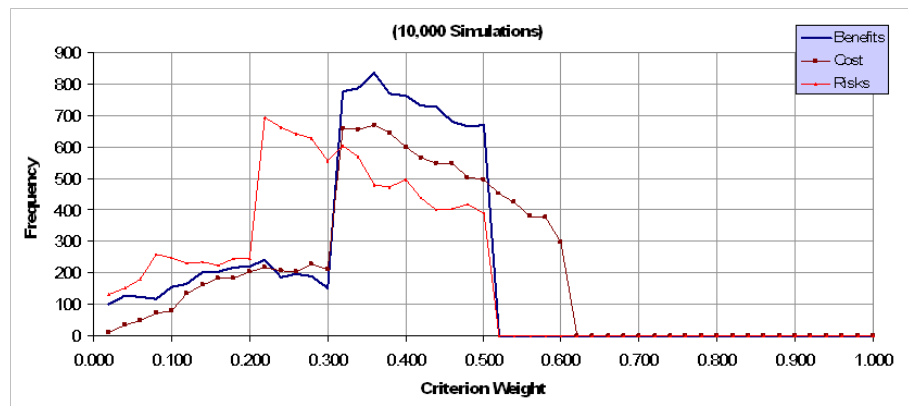


Figure 5.81: PDF of the BCR weighting scenario.

As discussed in the Presidential Helicopter experiment, it is expected that the uniform distributions include values lower than their respective lower range. This is due to the fact that the weighting criteria are dependent on each other, since their sum needs to be equaled to 1. By observing the PDF of Figure 5.81, one needs to understand that the results of the Monte Carlo simulations are slightly biased toward a higher benefit weighting, being caused by the higher frequency of the benefit weighting.

The other main results of the Monte Carlo simulations are the Cumulative Distribution Functions (CDF). Figures 5.82, 5.83, and 5.84 present the CDFs of the internal combustion engine, electric motor, and diesel engine configurations respectively.

The CDFs of the different configurations provide an indication of the range of the Synthesized BCR values, however the desired results that need to be inferred from these figures are the probabilities that the configuration benefits is greater than the sum of the costs and risks. For all of the alternative configurations, the probabilities of having a positive value for the synthesized BCR are listed in Table 5.13.

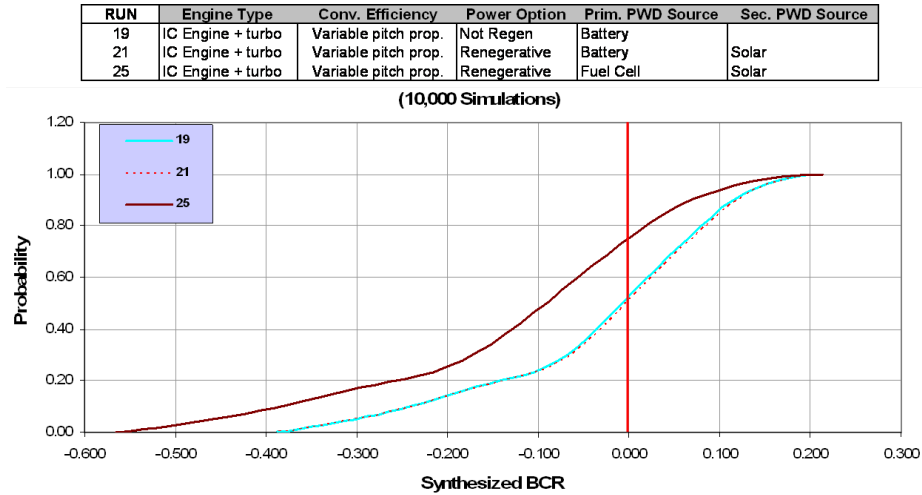


Figure 5.82: CDF of the IC engine motor configurations BCR.

Table 5.13: Probability of having a positive synthesized BCR value.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. PWD Source	Sec. PWD Source	Probability BCR > 0 (%)
19	IC Engine + turbo	Variable pitch prop.	Not Regen	Battery		45
21	IC Engine + turbo	Variable pitch prop.	Renegerative	Battery	Solar	46
25	IC Engine + turbo	Variable pitch prop.	Renegerative	Fuel Cell	Solar	23
65	Electric Motor	Variable pitch prop.	Not Regen	Battery		56
67	Electric Motor	Variable pitch prop.	Renegerative	Battery	Solar	57
69	Electric Motor	Variable pitch prop.	Renegerative	Battery	altitude	48
71	Electric Motor	Variable pitch prop.	Renegerative	Fuel Cell	Solar	29
75	Electric Motor	Variable pitch prop.	Hybrid	Battery	Solar	34
129	Diesel	Variable pitch prop.	Not Regen	Battery		40

From the results of the CDFs, it can be noticed that only two configurations have a positive synthesized BCR for more than 50 % of the times. Also, it should be noted that the most promising alternative observed before the propagation of the uncertainty only results in a positive synthesized BCR 29 % of the times, based on this specific weighting scenario. Therefore, the propagation of the uncertainty at this stage of the proposed methodology provides significant information reducing the epistemic uncertainty surrounding the system design.

The next part of the uncertainty analysis is to determine the influence of operational relative importance on the alternative configurations synthesized BCR values. For this uncertainty propagation, only the five most promising alternative configurations are used to propagate the uncertainty. Furthermore, since it is desired to capture only the variation of the operational elements, the weighting of the benefit, cost and risk criteria are fixed to the following values: $w_B = 0.45$, $w_C = 0.35$, and $w_R = 0.20$.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. PWD Source	Sec. PWD Source
65	Electric Motor	Variable pitch prop.	Not Regen	Battery	
67	Electric Motor	Variable pitch prop.	Renegerative	Battery	Solar
69	Electric Motor	Variable pitch prop.	Renegerative	Battery	altitude
71	Electric Motor	Variable pitch prop.	Renegerative	Fuel Cell	Solar
75	Electric Motor	Variable pitch prop.	Hybrid	Battery	Solar

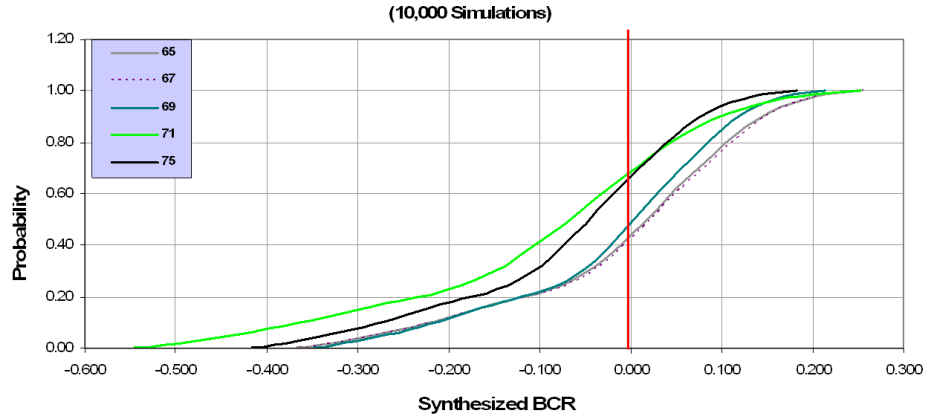


Figure 5.83: CDF of the electric motor configurations BCR.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. PWD Source	Sec. PWD Source
129	Diesel	Variable pitch prop.	Not Regen	Battery	

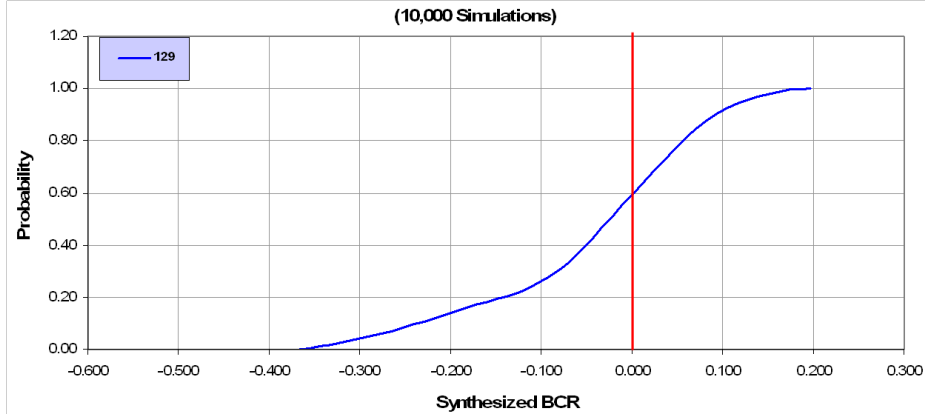


Figure 5.84: CDF of the diesel motor configuration BCR.

These weightings are selected based on the fact that the UAV will be used as a technology demonstrator, and consequently it can be expected that the benefits and costs dimensions are more important than the risk dimension. With this specific weighting scenario, Table 5.14 lists the initial synthesized BCR values without any operational uncertainty.

The assumptions used to propagate the operational uncertainty are the same as the one presented in Figure 5.68. For each Monte Carlo simulation, the relative importance of the propulsion and power systems MoEs is calculated and then combined with the synthesized benefit and cost of the alternative configuration to calculate the synthesized BCR value.

The uncertainty is propagated through 10,000 Monte Carlo simulations and the overall

Table 5.14: Alternative configurations used for operational uncertainty analysis.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. PWD Source	Sec. PWD Source	Initial BCR Value
19	IC Engine + turbo	Variable pitch prop.	Not Regen	Battery		0.0824
21	IC Engine + turbo	Variable pitch prop.	Renegerative	Battery	Solar	0.0877
65	Electric Motor	Variable pitch prop.	Not Regen	Battery		0.1067
67	Electric Motor	Variable pitch prop.	Renegerative	Battery	Solar	0.1121
69	Electric Motor	Variable pitch prop.	Renegerative	Battery	altitude	0.0857
129	Diesel	Variable pitch prop.	Not Regen	Battery		0.0563

Table 5.15: Operational uncertainty influence on the configuration BCR value.

RUN	Engine Type	Initial BCR Value	Min BCR Value	Max BCR Value	BCR Value Difference
19	IC Engine + turbo	0.0824	0.0790	0.0884	0.0093
21	IC Engine + turbo	0.0877	0.0845	0.0933	0.0088
65	Electric Motor	0.1067	0.0992	0.1189	0.0197
67	Electric Motor	0.1121	0.1046	0.1238	0.0192
69	Electric Motor	0.0857	0.0771	0.1030	0.0259
129	Diesel	0.0563	0.0542	0.0594	0.0052

variations of the synthesized BCR values are listed in Table 5.15.

It can be seen from this uncertainty analysis that the total variation synthesized BCR is close to 1 % in most of the cases. This variation is not large enough to result into a negative BCR value from a positive value. On the other side, the alternatives ranking may be affected by the operational uncertainty. By adding the total variation due to the uncertainty on the initial BCR value, the ranking between configuration 65 and 67 for the best two configurations is now intertwined. The same can be said for the third best alternative, where the total variation of configurations 19, 21, and 69 intersect each other.

The fact that there is no clear “winning” configuration can be expected at the requirement analysis phase, since more detailed technical analyses are necessary for the final selection of the vehicle configuration. On the other hand, reducing the number of alternatives during the requirements definition phase is helpful to focus the team effort on a few promising solutions. Also, since the different alternative configurations correspond to different system MoE values, that range of values can help the design team to narrow the threshold and goal values for the different systems MoEs.

In this section, the uncertainty was first propagated through the decision model. The results of this uncertainty analysis were visualized by the variation in ranking of the operational MoEs, systems and systems MoEs. The second part of this section discussed how the systems MoEs were mapped with the systems alternatives and therefore extending the traceability of the information to another level of the hierarchy. The third part of this section

consisted of propagating the uncertainty through the systems MoE and systems alternatives mapping. In this part the benefit, cost and risk dimensions of the alternative configurations were synthesized using the additive (negative) equation discussed in section 3.5.2.

In summary, the information gathered in this section has been proven useful to demonstrate that the choice of alternative configuration varies as a function of the criteria considered for the selection process, and the uncertainty surrounding these criteria. The benefit, cost and risk criteria are deemed well suited to map the systems alternatives with the decision model, and provided significant information that can be used to reduce the epistemic uncertainty of the project.

5.3.5 Step 6: Create Requirements Statements and Allocate Resources

The last step of the proposed methodology is to synthesize the knowledge gathered from the five previous steps to create the requirements statements. The activities included in this step are represented in Figure 5.85.

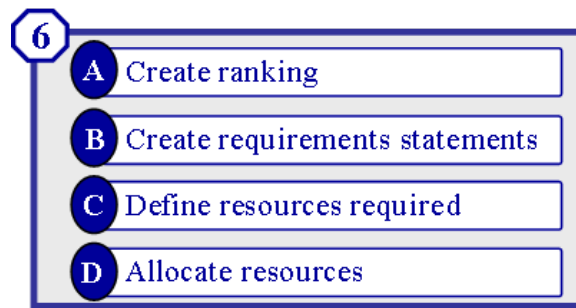


Figure 5.85: Step 6: Activities involve in the requirements statements and resource allocation.

The first activity is to create the ranking of the different elements of the hierarchical model (**activity 6-A**). This activity was performed in steps 4 & 5 (section 5.3.4) to demonstrate the influence of the uncertainty on the variability of the rankings. Depending on the level of importance of the operational and system MoEs, some elements may be discarded while others can be added to the hierarchical model.

Subsequently, by going through the proposed methodology steps, more information is gathered and stored with respect to the importance of the operational and systems MoEs for the success of the project. These steps allow the design team to structure their decision

making process in order to select, at the end of the conceptual design, a final vehicle configuration. The knowledge acquired through the proposed methodology can now be used to create the well-formed requirement statements (**activity 6-B**) first discussed in section 2.1. As a reminder, a well-formed requirement includes a capability (expectation or function), attributes (MoEs), and (if necessary) constraints.

Since the goal of this experiment was to implement the proposed methodology to a UAV design problem, and not to perform the entire conceptual design of the vehicle, a sub-set of the systems MoEs was analyzed in more detail. From this sub-set, well-formed requirement statements can be created and are listed in Table 5.16.

Table 5.16: Propulsion system requirement statement.

Propulsion System	Statement	Threshold	Goal
Capability	The system shall convert the bulk source of energy into mechanical work to provide thrust.		
Attribute	The system specific power corresponds to the amount of Watt produced by 1 kg of the system (W/kg)	164	222
	The energy consumption is defined as the amount of energy needed for a specific thrust value over period of time (g/(kW-h))	80	57
Constraint	Propulsion system mass	TBD	TBD

Table 5.17: Power system requirement statement.

Power System	Statement	Threshold	Goal
Capability	The system shall provide the electrical energy for the entire vehicle		
Attribute	The specific power corresponds to the amount of electrical energy produced by 1 kg of the system (kW/kg)	0.1	0.5
Constraint	Power system Mass	TBD	TBD

For both of these requirement statements more constraints can be added as more analysis is performed, for instance the discharge rate could be added for the power system statement. The threshold and goal values of the mass constraints also require more information specific to the vehicle sizing. However, these constraints values are not expected to influence the capability and attribute statements.

The operational requirement statements are not discussed in this section since they would have required the analysis of the airframe MoEs to determine how well the vehicle can fly

Table 5.18: Alternative configuration estimated costs.

RUN	Engine Type	Conv. Efficiency	Power Option	Prim. Source	Sec. Source	Cost (\$k)
19	IC Engine + turbo	Variable pitch prop.	Not Regen	Battery		1079
21	IC Engine + turbo	Variable pitch prop.	Renegerative	Battery	Solar	1064
65	Electric Motor	Variable pitch prop.	Not Regen	Battery		1074
67	Electric Motor	Variable pitch prop.	Renegerative	Battery	Solar	1060
69	Electric Motor	Variable pitch prop.	Renegerative	Battery	altitude	993
129	Diesel	Variable pitch prop.	Not Regen	Battery		1072

the mission. For example the mapping of L/D, wing area and wing aspect ratio to specific vehicle configurations would be required to determine their relative importance with respect to the cruise speed, endurance and range. That mapping between the other systems MoEs and the systems alternatives, can be performed using the same activities of the proposed methodology as discussed in this section.

The next activity of Step 6 (**activity 6-C**) is to identify the required resources. With the mapping between the system MoE and the systems alternatives, an estimated cost value has been calculated, as listed in Table 5.18.

These cost values are resulting from both quantitative information (existing system costs), and qualitative information. The qualitative information is associated with the cost decision model that is divided between the development, manufacturing and operating costs. In this experiment, only monetary values have been used as resources. However, the cost decision model could have been further divided to include the schedule (time) and technology (monetary) resources.

Finally, if all the systems MoEs are mapped with systems alternatives, then it is possible to estimate the overall costs of the project. If the overall cost is greater than the available resources, then the design team can use the ranking of the operational and systems MoEs to allocate the resources to the most important systems in order to satisfy the most important stakeholder expectations. This step of the process needs to be clearly described during the first design review, so that at the end of the review the stakeholders expectations are mapped with the desired systems as a function of the available resources.

5.4 Closing the Requirements Analysis Process

The purpose of this research is to identify and define complex systems requirements. As the design team goes through the proposed methodology steps, new information is elicited to identify the most important functions and MoEs in order to create the well-formed requirement statements. In addition, quantitative information from the exploration of the matrix of alternatives is used to establish threshold and goal values for the requirements statements. However in order to generate feasible and viable alternatives, the design team needs to perform further analysis on the systems before fixing the requirements values. This process is illustrated within the Georgia Tech Integrated Product and Process Development (IPPD) framework shown in Figure 5.86 [162].

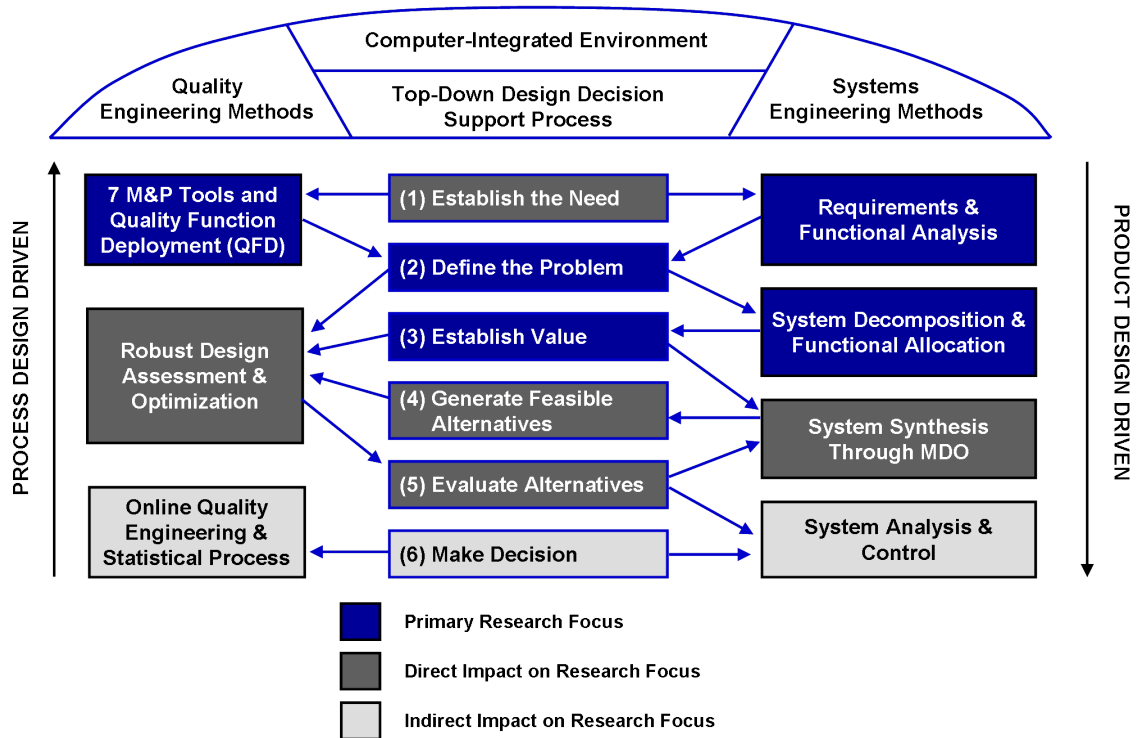


Figure 5.86: Georgia Tech IPPD framework.

The primary focuses of this research are emphasized in Figure 5.86, they include the definition of the problem (2) and the evaluation of the requirement's values (3) by using quality and systems engineering methods. Some elements of the IPPD framework are directly influencing this research either by providing information used in the proposed methodology

or by using the results of the proposed methodology within other methods. The tight coupling between the elements of the IPPD process implies that the entire framework is needed to ensure the selection of a feasible system alternative.

With respect to this research, the objective of this section is to illustrate how system sizing and synthesis information can be used to provide more quantitative information to the requirements mapping. Consequently, this step corresponds to the “*system synthesis*” and “*generate feasible alternatives*” of the IPPD process.

5.4.1 UAV Design Environment

The system synthesis and generation of feasible alternatives activities require a design environment. Within this design environment, the physical dimensions of the systems are scaled (sizing), while multi-disciplinary analysis tools use these dimensions to evaluate the system’s performance (synthesis). The process iterates between the sizing and synthesis until the requirements are matched in terms of power, energy and geometry [129]. This section presents the UAV design environment used in this research to evaluate the quantitative relationships between the operational and systems MoEs.

This UAV design environment has been created in order to take advantages of the various disciplinary analysis tools available to the design team [48]. Table 5.19 lists the different disciplinary tools implemented in the design environment. The variable-fidelity capability enables the user to balance the complexity of the analysis against the required run-time by selecting which level of fidelity is appropriate for each discipline.

Table 5.19: UAV environment multi-disciplinary tools.

		Discipline					
		Geometry	Airfoil	Aerodynamics: Friction Drag	Aerodynamics: Lift & Induced Drag	Structures	Propulsion
Fidelity	Low	2D Model	PABLO	Form factor relationships	Lifting line	Regressed equations	Table look-up
	Medium	VSP (3D)	XFOIL ^(GNU)	Airfoil numerical integration	VORLAX (Vortex Lattice)	DYMORE [®] (static)	Matlab/Simulink modules [®]
	High	CATIA V5 [®]	Experimental data	CFD - Fluent [®]	CFD - Fluent [®]	DYMORE [®] (dynamic)	Experimental Data
	High Off-Line		CFD - Fluent [®]		CFD - Fluent [®]		

Implemented
 Not implemented

The design structure matrix of the UAV design environment is shown in Figure 5.87.

The main inputs of the environment include a baseline geometry, an operational mission, the design flight conditions and the preferred sizing strategy. Once the inputs are defined, the user selects the desired airfoil analysis tool to evaluate the aerodynamic coefficients, Figure 5.87 (step 1).

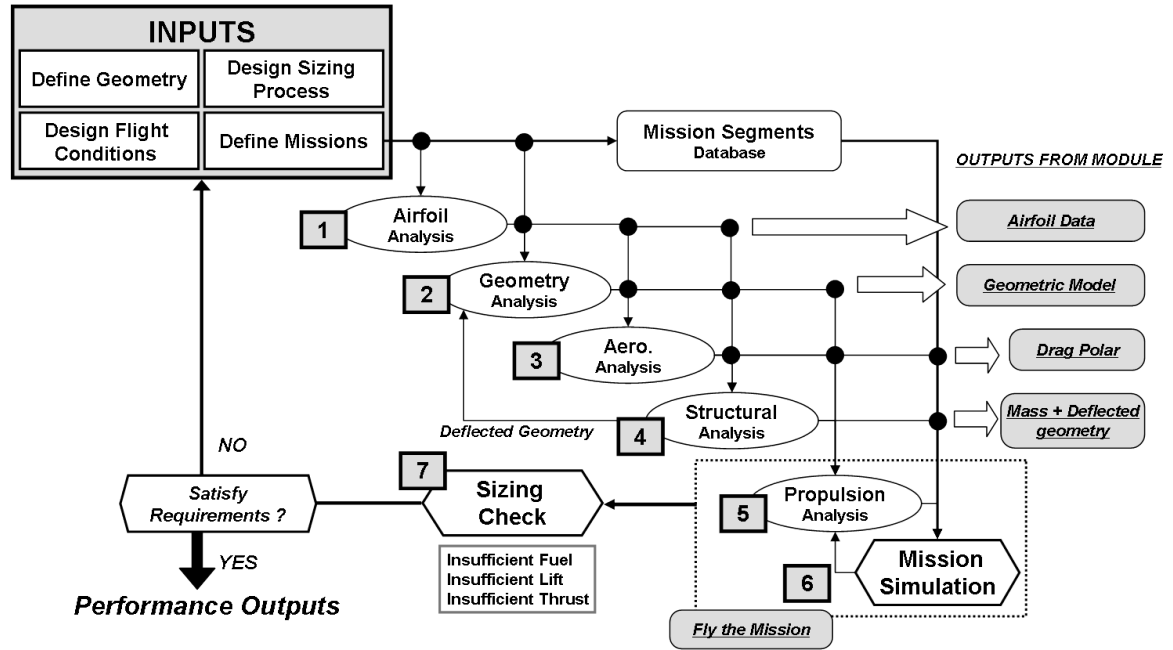


Figure 5.87: UAV environment design structure matrix.

The user has the choice between PABLO [148], XFOIL [46] or experimental data, if they are available. PABLO is relatively fast and accurate for inviscid flow, while XFOIL is fast and accurate for both inviscid and viscous flow. Multiple airfoil analyses can be performed, and the results are stored in text files accessible to the aerodynamics and structural modules. The second step shown in Figure 5.87 is to model the geometric variables in a Computer Assisted Design (CAD) software. The CAD tool used in the environment is the NASA developed Vehicle Sketch Pad (VSP) which is an extension of the Rapid Aircraft Modeler (RAM) [60]. This tool includes a set of predefined aircraft parameters for wings, fuselages, and pods, and also calculates the wetted area of the individual geometric elements for friction drag calculations. Using the baseline geometry, VSP computes lift, induced drag and aerodynamic moments through a vortex lattice solver called VORLAX [125], Figure 5.87 (step 3). Analyzing a complex geometry in VORLAX can be time consuming. For that

reason a numerical lifting line code [36] was added to the aerodynamics module to compute the lift and induced drag of a simple wing design. The drag breakdown is completed with the evaluation of friction drag using either airfoil data or form factor empirical relationships [115]. The form factor code is based on empirical equations that are a function of the Reynolds number and the wetted area of the individual components. The airfoil approach requires the numerical integration of the airfoil sectional drag over the lifting surface. This technique has been coded in MATLAB® and requires the use of the airfoil analysis results previously calculated. The vehicle aerodynamics coefficients are also stored in a text file that is used during the mission simulation (step 6).

Once the aerodynamic characteristics of the vehicle are computed, the information is transferred to the structures module to evaluate the deflected geometry, Figure 5.87 (step 4). The structures module calculates the wing deflections, wing weight and root stresses based on an equivalent beam having pre-defined cross-sectional properties. The cross-sectional properties are obtained using VABS© (Variational Asymptotical Beam Sectional Analysis) [200]. The properties are then used as inputs to DYMORE©, which performs a structural analysis of the equivalent beam giving the wing deflections and root stresses [15]. The actual weights calculation can be performed by summing the resulting structural masses or from empirical wing data [144, 149]. The option is then provided to iterate back with the structurally deflected geometry to update the geometry model and re-evaluate the aerodynamic characteristics.

The propulsion module, Figure 5.87 (step 5), includes six propulsion architectures combining power systems, propulsive systems and Power Management And Distribution (PMAD) systems. The propulsion architectures are listed in Table 5.20.

Table 5.20: UAV propulsion architectures modeled in design environment.

#	Power System	PMAD
1	Solar cell and fuel cell	Electrolyzer, H ₂ tank, O ₂ tank and H ₂ O tank
2	Fuel cell	H ₂ tank, O ₂ tank
3	Solar cell and fuel cell	Electrolyzer, H ₂ tank, O ₂ tank
4	Solar cell and fuel cell	H ₂ tank and centrifugal compressor
5	Solar cell	Rechargeable battery pack
6	Hydrogen internal combustion engine	H ₂ tank and centrifugal compressor

The propulsive system is identical for all architectures; it includes either electrical motors or internal combustion engines with gearbox and propeller models. The propulsion architectures are modeled in MATLAB Simulink® and integrated into a ModelCenter® environment. The selection of the desired propulsion architecture is an input to the design environment.

5.4.2 From UAV Design Environment to Requirements Mapping

The objective of this section is not to select the final vehicle configuration, but to demonstrate how the system’s sizing and synthesis can be used to provide more information to the requirements analysis process. Consequently, for the UAV experiment a baseline UAV configuration is chosen to explore the relationships between the operational and systems MoEs. More specifically, the relationships between the operational MoE “*time on station*” and the airframe system MoEs (*L/D*, *wing area*, *wing aspect ratio* and *total weight*) are explored with the design environment.

The baseline configuration used in this section corresponds to the AeroVironment Pathfinder Plus UAV geometry combined with a regenerative power system including a Proton Exchange Membrane (PEM) fuel cell, an electrolyzer, and solar panels. The wing geometry dimensions and the propulsion systems assumptions are listed in Table 5.21.

Table 5.21: Pathfinder Plus geometric and propulsion variables[130].

Geometric variable	Dimension	Propulsion variable	Value
Chord (m)	2.4	Number of engine	8
Span (m)	36.9	Motor Power (kW) each	1.5
Wing Aspect Ratio	15	Total Power Output (kW)	12.5
Airfoil central section	Selig S6078		

Using the Pathfinder Plus dimensions, the geometric model is created within VSP and used as input to the UAV design environment. The CAD representation of the vehicle is shown in Figure 5.88.

The operational mission is the other main input to the design environment. For this experiment the goal is not to perform the complete hurricane-tracking mission but to explore the relationships surrounding the operational MoE “*time on station*”. Consequently, a

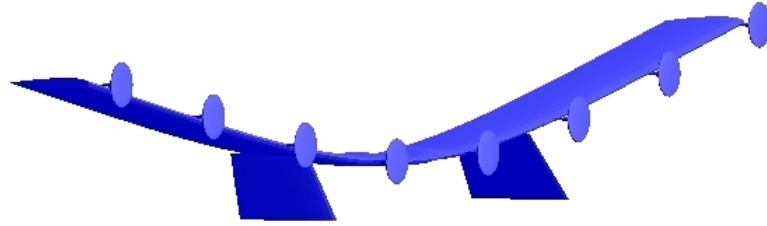


Figure 5.88: Pathfinder Plus UAV in VSP.

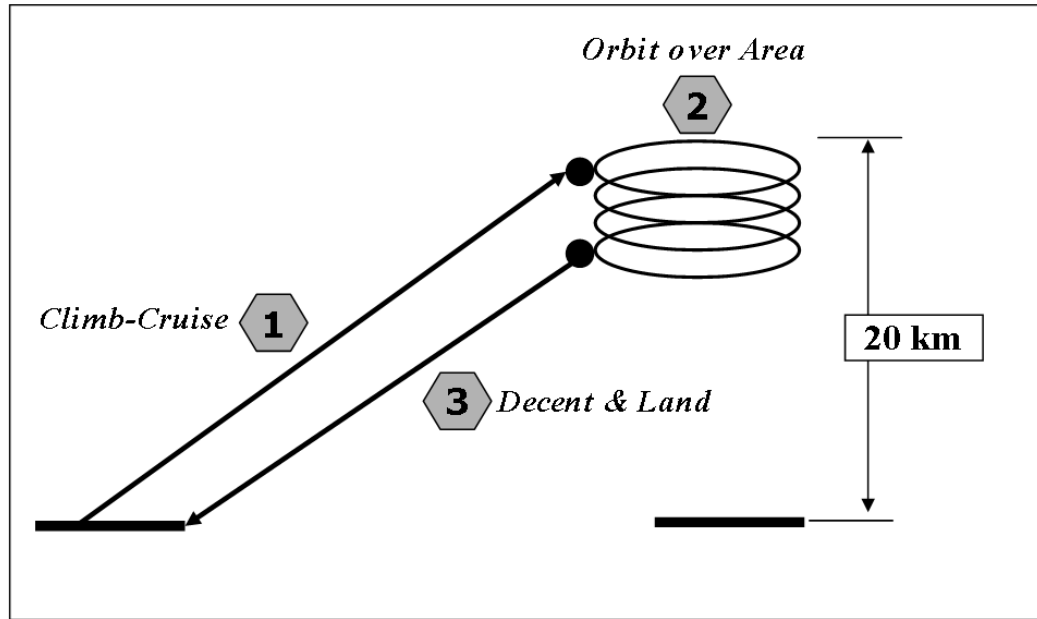


Figure 5.89: Time on Station mission.

specific mission is created requiring the UAV to climb to a defined altitude and then loiter until all the hydrogen is transformed into water produced by the PEM fuel cell, see Figure 5.89. Note that the initial mass of hydrogen has been fixed to 3.5 kg to ensure that the UAV will run out of fuel and not stay aloft indefinitely. In other words, the energy required by the electrolyzer to transform the water produced by the fuel cell into hydrogen is greater than the energy produced by the solar panels; therefore the mass of hydrogen decreases over time.

With the baseline geometry and the operational mission, the objective is to vary the airframe system MoEs to explore the design space. Table 5.22 lists the system MoEs that are varied within the design environment. The variation of the payload weight and drag

coefficient are used to assess the relative importance of the overall weight and the vehicle's drag polar on the time on station respectively.

Table 5.22: Design space exploration for *Time on Station* MoE.

Number	Variable	Description	Baseline	Min	Max	Units
1	Sref	Wing Area	91	60	120	m ²
2	AR	Aspect Ratio	15	12	25	~
3	Wpld	Payload Weight	67.5	30	100	kg
4	$\Delta \mathbf{C}_D$	Δ Drag coefficient	100	85	115	% \mathbf{C}_D

Response Surface Methodology (RSM) is used to explore the design space [41]. This methodology utilizes Design of Experiments (DOE) to regress a polynomial model, typically second order, based on the design variables selected by the design team. The form of the second-order equation, referred as Response Surface Equation (RSE), is depicted in Eq. 5.5.

$$R = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k \beta_{ij} x_i x_j \quad (5.5)$$

For this experiment, R corresponds to the time on station in hours, x_i are the design variables representing the system MoEs, and β values corresponds to the coefficients of the polynomial regression. Consequently, it is possible to use the RSE of the time on station to analyze the relative importance of the system MoEs and compare this quantitative mapping with the qualitative mapping described in section 5.3.3.

A 25-case face-centered Central Composite DOE is created to determine which combination of the system MoE values should be run in the UAV design environment. An additional 10 cases, including randomly generated values between the design variable ranges, are used to validate the RSE. For each 35 DOE cases, the geometry of the UAV is modified, a new drag polar is calculated, and then the UAV fly the operational mission to evaluate the time on station value.

With the results from the UAV design environment, the RSE is regressed using the commercially available JMP® statistical software suite. The actual (UAV design environment) versus predicted (RSE) time on station responses are illustrated in Figure 5.90. From this figure, it can be seen that the RSE is capturing 99% (R^2) of the variability of the response.

The area between the red dashed lines represents 95% of the variability of the response.

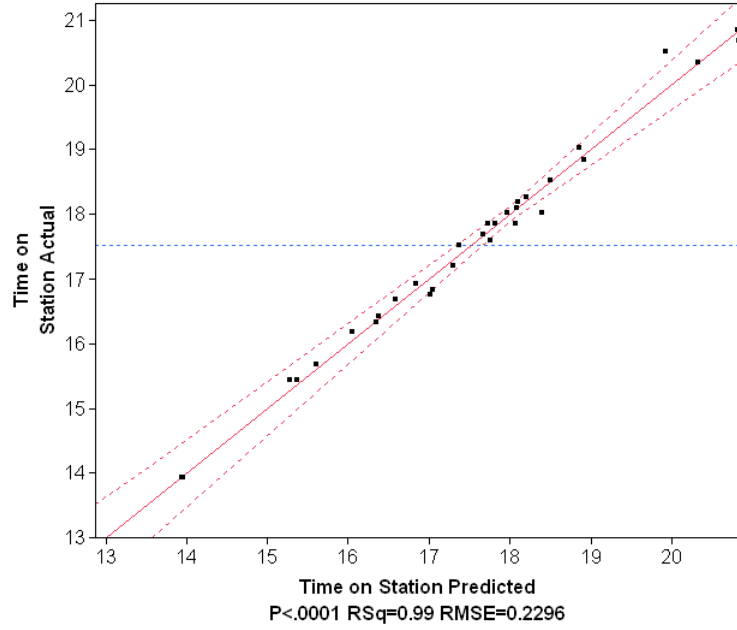


Figure 5.90: Time on Station RSE: Actual vs. Predicted value

From Figure 5.90, it can be observed that the vehicle configurations considered have an endurance ranging from 13 to 21 hours. From the same surrogate model, it is possible to analyze the influence of the airframe system MoEs through a prediction profiler tool, see Figure 5.91.

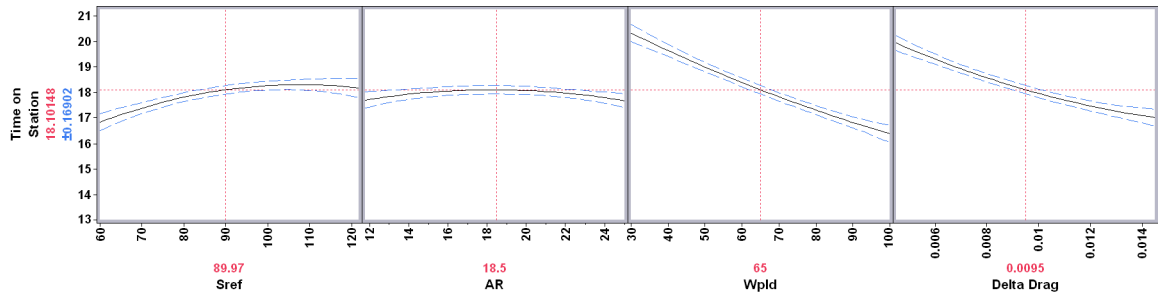


Figure 5.91: Prediction profiler: Time on Station vs. System MoEs.

The prediction profiler allows the user to dynamically vary any of the system MoE, and visualize the impact of the change on the time on station. More importantly, the user can visualize the trends between the response and the system MoEs. For instance, it can be seen that as the wing area increases the time on station also increases, while as the payload weight and the drag coefficient increase the time on station decreases. For the wing aspect ratio (**AR**) there is a nominal value that maximizes the time on station. This is due to

the fact that a small AR implies more induced drag (\downarrow time on station), whereas large AR implies a heavier wing (\downarrow time on station). This type of information was not available during the creation of the decision model in section 5.3.3.

The quantitative information from the UAV design environment and the RSE can then be fed-back to the decision model by analyzing the relative importance of the system MoEs on the time on station. Figure 5.92 presents the system MoE coefficients (β 's) from the RSE under the “*Estimate*” column.

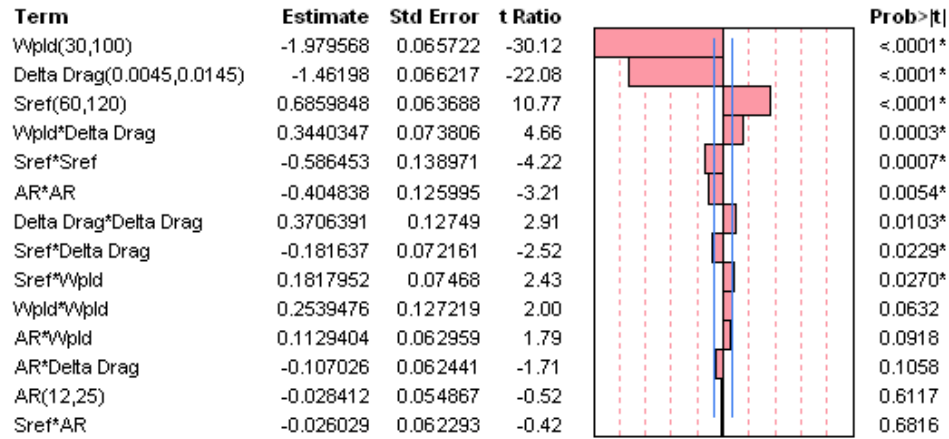


Figure 5.92: Relative importance of the systems MoE variables.

By taking the partial derivative of the response (R) with respect to a given system MoE (e.g. x_1), see Eq. 5.6, the estimate value (β_1) represents the main linear effect of that system MoE with respect to the response.

$$\frac{\partial R}{\partial x_1} = \beta_1 + 2\beta_{11}x_1 + \sum_{j=i+1}^k \beta_{1j}x_j \quad (5.6)$$

From Figure 5.92, it can be seen that the main linear effects of the payload weight ($Wpld$), ΔC_D (*Delta Drag*), and wing area (*Sref*) have the largest absolute amplitude of the RSE. Therefore, the estimate values can be viewed as a measure of the relative importance of the system MoEs with respect to the variability of the response. By normalizing the four system MoE estimate values using the L1 norm, the user obtains quantitative relative importance of the airframe system MoEs with respect to the operational MoE time on station.

Table 5.23 compares the qualitative and quantitative relative importance of the airframe

system MoEs with respect to the time on station.

Table 5.23: Comparison between qualitative and quantitative system MoE priority.

System MoE	Qualitative Priority	Quantitative Priority
Drag polar (C_L/C_D)	0.232	0.352
Total weight	0.140	0.476
Internal Volume	0.400	~
Wing AR	0.232	0.007
Wing Area	~	0.165

In the qualitative mapping the internal volume was considered important because of its influence on the payload capacity and aerodynamics coefficients. Larger volume implying more payload (more weight) which would reduce the time on station; also larger volume implying more wetted area which would increase the friction drag of the vehicle and decrease the time on station. Consequently this system MoE was considered important because of its combined impact on the vehicle. Furthermore, in the qualitative mapping the wing AR was considered to include the influence of the wing area and consequently the wing area was not included in the mapping.

Regarding the quantitative mapping, the user is often limited to analyze the relationships embedded in the design environment. For instance, in the UAV design environment the internal volume is not modeled as a function of the payload mass and volume, consequently it was not included in the quantitative mapping. By exploring the time on station design space, based on the pre-defined ranges of system MoEs, it was possible to evaluate the relative importance of the system MoEs by using the coefficients of the surrogate model. The relative importance indicated that the total weight and the vehicle's aerodynamics are strongly influencing the time on station of the UAV. The total weight had the greatest importance in the quantitative mapping, whereas it was judged to be least important MoE in the qualitative mapping. Furthermore, since both wing area and AR relationships are available in the UAV design environment, it was possible to observe that the maximum time on station is obtained at a nominal AR value. This information was not captured in the qualitative mapping, and should be taken into account in the definition of the wing's requirements.

In conclusion, this comparison analysis shows the importance of using both qualitative and quantitative information in the requirements analysis process. Not all relationships are modeled in a design environment, and consequently qualitative mapping is often the only alternative for the design team. On the other hand, when a relationship is modeled in a design environment, the physics or historical data behind the relationships provide a more accurate representation of the relative importance of the variables. This information should then be fed-back to the requirements mapping process in order to substantiate the decision model with more quantitative information.

5.5 Contributions of Proposed Methodology

The objective of this section is to emphasize the advantages and contributions of the proposed methodology with respect to the most utilized requirements definition and modeling process. Through the literature, it has been observed that the QFD process is one of the most popular requirements mapping approach utilized in the industry and the academia. Figure 5.93 schematically compares the current requirements mapping approach (including the QFD process) with the proposed methodology. The advantages and contributions of the proposed methodology are regrouped under the following three categories that will be described in this section:

-
1. Overall **traceability** of the elements included in the requirements analysis process
 2. Evaluation of the **consistency** of the qualitative comparisons
 3. A structured process to utilize available **quantitative information**
-

5.5.1 Traceability in the Requirements Mapping

The traceability of the requirements information was described in section 3.1.2 as one of the most important requirement properties. The traceability in the flow of information is important, because it allows the user to understand the origin of the requirements, and the information linked to the requirements often dictates their level of importance.

In the current requirements mapping process illustrated in Figure 5.93, a large amount of information is gathered and acquired while defining the requirements and the functional

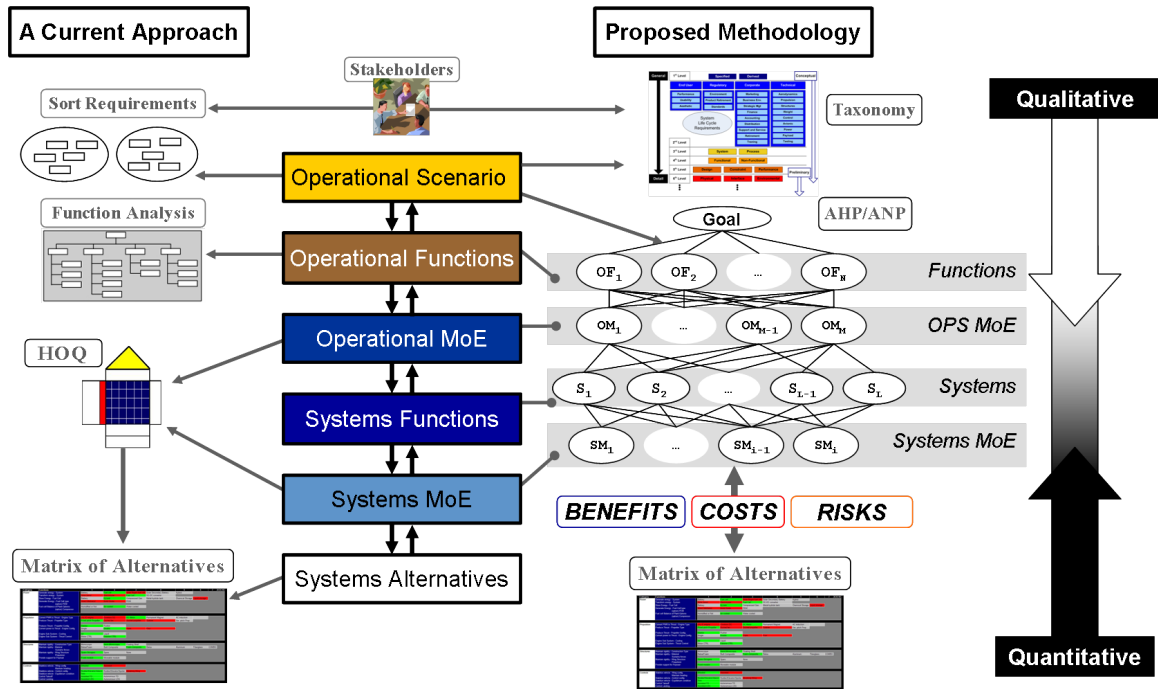


Figure 5.93: Comparison between a current approach and the proposed methodology.

analysis of the systems. This information is then used in the QFD process to map the requirements with the engineering characteristics in the HoQ. In the literature review of section 3.3.2, no structured process was identified to trace the problem definition information to the QFD process. The traceability of the information is limited to a specific activity, which makes it difficult to understand the origin of the requirements. This is a major problem because the design team cannot question the assumptions behind the formulation of the requirements, which makes it hard to judge the validity of the requirements.

At this point one may wonder: how can the problem definition information be used in the HoQ? The answer to this question is during the definition of the requirement's relative importance. In the HoQ, the relative importance of each requirement is established on a subjective scale ranging from 1 (low importance) to 10 (very important) [65]. The design team subjectively defines these relative importance values based on experience or previously acquired information. From an external observer perspective, it is extremely difficult to understand the origin of these relative importance values without having to ask the design team.

Subsequently, the requirement's relative importance values are used to determine the relative importance of the engineering characteristics through the relationships matrix. Therefore, if a bias is introduced at the requirement's level, then this bias will affect the ranking of the engineering characteristics, which may later bias the selection of the system alternatives.

Furthermore, the QFD process is decoupled from the analysis of alternatives process, which also breaks the traceability of the information. In the literature review of section 3.3.2, some publications used the relative importance from QFD to down-select the number of alternatives, however this process was performed on a much simpler scale, including only a handful of systems alternatives. In the literature, there was no reference to such a process implemented to a large morphological matrix including a very large number of alternative configurations.

5.5.1.1 Advantages and Contributions of the Proposed Methodology

The proposed methodology allows the user to classify and manage the problem definition information with a unique taxonomy. The taxonomy, defined in section 4.2, allows the design team to understand if the requirements was specified or derived (level 1), the associated stakeholders (level 2), and the associated system, process or operation (level 3). All the information required for the creation of a well-formed requirement statement can be stored and retrieved from the taxonomy.

In Figure 5.93, it can be seen that the requirements mapping of the proposed methodology is divided in multiple levels. The importance of the elements of a lower level are influenced by the relative importance of the higher level elements. Consequently, it is possible for an external observer to understand why an operational MoE is more important than another one, by analyzing the relative importance of the higher levels elements and their mapping with the current level elements. Based on this type of analysis, the external observer can approve or question the validity of the assumptions leading to the creation of the requirement statements.

In the proposed methodology the traceability in the requirements mapping is extended to the matrix of alternatives through a benefits, costs and risks model. This capability

allows the relative importance values of the systems MoEs to be directly linked to the system alternatives. As described in section 5.3.4, an algorithm was created to explore all compatible alternatives of the morphological matrix, which allows the decision makers to compare (and eventually to down-select) alternatives based on a set of sub-level criteria synthesized within the benefits, costs, and risks hierarchies. This contribution of the proposed methodology enables the design team to perform a structured down-selection of alternatives while taking into account the relative importance defined previously.

Another advantage enabled through the overall traceability of the information is the ability to propagate the uncertainty from any level of the requirements mapping. Consequently, the design team can evaluate multiple weighting scenarios in order to analyze the relative importance variability of the lower level functions and MoEs. As discussed in section 5.3.4, the knowledge acquired through the uncertainty analysis reduces the epistemic uncertainty surrounding the requirements definition process.

Here is a summary of the advantages of the proposed methodology:

1. Information stored and managed with a unique taxonomy;
2. Continuous traceability of information helps to understand the origin of the requirements definition;
 - i. Relative importance depends on higher-level elements;
 - ii. Uncertainty scenarios can be propagated through the requirements mapping;
3. Quantitative information from the system alternatives exploration can be used to substantiate the requirements mapping.

5.5.2 Qualitative Comparison Consistency

At the conceptual design, the absence of quantitative model and the low level of knowledge favors the use of qualitative relationships. In the HoQ , the relationships between the requirements and the engineering characteristics are defined in terms of “*strong*”, “*medium*” or “*weak*” relationships. For each requirement, the design team goes through the list of engineering characteristics to define the strength of the relationships.

It has been established, through many applications, that the QFD process emphasizes team work and improves the communication during the conceptual design process. However, there is no process within the QFD allowing the design team to verify the consistency of their qualitative comparisons. Furthermore, the qualitative scale used in the HoQ makes it difficult for the design team to use quantitative information, from historical data or from sizing and synthesis results, in order to compare and verify the qualitative relationships.

5.5.2.1 *Advantages and Contributions of the Proposed Methodology*

In the proposed methodology, the consistency of the qualitative comparisons can be verified with a consistency ratio. The consistency ratio is a key feature of the Analytic Network Process. The theory enabling the evaluation of the consistency ratio is based on the pairwise comparisons and the fundamental scale as described in section 3.3.3.

Identifying inconsistencies within the qualitative relationships forces the design team to question that validity of previous pairwise comparisons. By doing so, it generates discussions within the team, favoring communication, and allows the team members to hypothesize on inconsistency sources, which may bring additional information and knowledge to the design problem.

In addition the proposed methodology takes advantage of available quantitative information (section 5.3.4) or results from design environment (section 5.4) to replace or validate the previously made quantitative comparisons. That contribution is further emphasized in the next section.

5.5.3 **Quantitative Information**

Quantitative information, as discussed in section 3.3, can be based on historical data, empirical relationships, physics-based models or surrogate models. In the current approach, quantitative information can be found in both the QFD process and the matrix of alternatives. Dieter states that the main objective of the QFD process is “... *that the customer’s requirements be expressed as measurable design targets in terms of engineering parameters*”[45]. The HoQ includes quantitative information through the benchmarking of existing (competitive) alternatives.

The benchmarking is used to identify design ranges for engineering characteristics, and also to identify potential opportunity for system improvement. Then based on the knowledge acquired through the QFD process, the design team creates a matrix of alternatives from existing and future system alternatives. The matrix of alternatives structures the top-level system into category of functions while listing alternatives for each function. The system alternatives may include available quantitative information (i.e. performance, weight or cost) either from historical data or from previous modeling results. This information can be used to down-select the number of system configurations.

As discussed in section 5.3.2.1, the initial number of systems configurations is very large, and a first down-selection based on risk, cost, schedule and technology level is required to reduce the number of combinations. With the remaining number of systems configurations, the design team can use a design environment to explore the design space, while identifying achievable requirements threshold and goal values. This step is required in order to ensure that the final system configuration will be technically feasible and economically viable.

This current approach does not take full advantage of the presence of quantitative information. First, the quantitative information from the QFD, matrix of alternatives and design environment is not linked from process to process. Consequently the quantitative information is generally only used as guidelines and not directly integrated in the requirements mapping. Second, the relationships identified in the QFD process (i.e., relative importance) are not directly used to help the down-selection of alternatives. Third, type of scale used in the QFD makes it difficult to use quantitative information to validate or replace previously made qualitative comparisons. These drawbacks from the current approach are improved with the proposed methodology.

5.5.3.1 Advantages and Contributions of the Proposed Methodology

In the proposed methodology, a structured process has been created to take advantage of available quantitative information. This capability is possible because of the ratio scale used in the ANP process (section 3.3.3). Ratio scale or relative scale can use both qualitative and quantitative information to compare alternatives. Therefore, quantitative information

(when available) can be used at any level of the requirements mapping.

In the proposed methodology, the requirements mapping is directly linked to the matrix of alternatives through a benefits, costs and risks model. This important capability enables the results of the vehicles sizing and synthesis to be fed-back to the requirements mapping. This provides a significant source of quantitative information that can be used to validate or replace previously made qualitative comparisons. By doing so, the design team can re-evaluate the relative importance of the requirements mapping elements, and assess how the quantitative information influence the down-selection of system alternatives.

This contribution of the proposed methodology enables an iterative process between the requirements and systems analyses. The design team can substantiate the decision process with more quantitative information as before by using performance and costs results from historical data and/or available design environment.

Chapter VI

DISCUSSIONS AND CONCLUSION

The focus of this research is about the development of a methodology enabling the definition and modeling of complex systems requirements, while taking into account both the operational and system aspects of the problem. The requirements correspond to the fundamental building blocks of a new project, and as the systems are becoming more and more complex, it becomes difficult and ambiguous to first define the requirements and then to design the systems. The proposed methodology answers a growing need for a structured process allowing the matching of the stakeholders expectations with the systems requirements as early as possible in the design process. This need has been observed through the U.S. General Accounting Office publications, and by the development of new acquisition reforms by governmental entities.

More specifically, three research objectives were formulated in Chapter 1 based on top-level observations of the current processes used in the industry. These three research objectives are recalled here:

Objective 1: Improve the requirements mapping process by matching stakeholder expectations with functions, systems and resources. The requirements mapping should also help the transition between qualitative and quantitative analyses.

Objective 2: Reduce the requirements uncertainty by having a structured approach allowing requirements traceability in the mapping. The uncertainty shall also be reduced by taking into account the brain channel capacity limitation, which also has an impact on the consistency during relative comparison.

Objective 3: Improve the requirement selection process by taking into account established criteria and available resources. The resources can include tangible (monetary) and intangible (risks, safety) aspects.

From these research objectives, the scope of this work was further refined in Chapter 2 by reviewing existing requirements analysis methodologies. The scope definition resulted in the six research questions that guided the creation of the proposed methodology. In order to answer these research questions, Chapter 3 presented a literature review of existing tools and techniques that had the potential of being integrated to the proposed methodology. Based on this literature review, specific hypotheses were formulated to answer the research questions. Finally in Chapter 5 the hypotheses were implemented to analyze for their effectiveness of answering the research questions.

This chapter is meant to revisit these research questions and hypotheses, summarize the research contributions and recommend future research.

6.1 Revisiting Research Questions and Hypotheses

The research questions and hypotheses are at the core of this research. In the first part of this document, the motivation, research objectives and scope definition led to the formulation of the research questions, while the literature review led to the formulation of the hypotheses. The hypotheses represent solution paths taken to answer the research questions, and they are embedded within the proposed methodology.

6.1.1 Revisiting Research Question 1 & Hypothesis 1

The first research question refers to the different types of requirements. Different fields of engineering utilize different types and definitions for their requirements. Also in the literature, several requirements properties have been established to facilitate their verification and validation process. Consequently, to provide a uniform nomenclature for this research, different types of requirements have been defined in section 3.1. Realizing that the requirements mapping needs a structure to initiate the process, the first research question was formulated:

Research Questions 1: How to classify the requirements with respect to the stakeholders, functions, and systems?

In section 3.2, different taxonomies of requirements are reviewed to analyze their potential applicability to the proposed methodology. From this literature review the first hypothesis was formulated:

Hypothesis 1: The stakeholders, requirements, and systems can be classified under a single taxonomy.

This hypothesis represents an intermediary step between the definition of the problem and the modeling of the requirements. The main objective of the first hypothesis is to organize the mass of information coming from the problem definition in order to improve the requirements management process and to facilitate the transition of information to the requirements modeling process. Classifying the information based on a single taxonomy correspond to Step 1 of the proposed methodology.

In Chapter 5, the requirements taxonomy created in this research was applied to two experiments: (1) Presidential helicopter, and (2) hurricane tracking UAV. From these experiments, the taxonomy was proven useful during the brainstorming exercise to generate an initial list of expectations and MoEs. For instance, the hierarchy created for the Presidential helicopter survey is resulting from a brainstorming exercise based on the requirements taxonomy. For the second experiment, the taxonomy was also used during a brainstorming exercise but more so to manage the different functions and MoEs.

6.1.2 Revisiting Research Questions 2 and 3 & Hypothesis 2

The second and third research questions refer to the definition and modeling of the requirements. They are meant to address the first two research objectives, and they are associated with the second, third and fourth steps of the proposed methodology.

From the problem definition, a large amount of information is gathered to provide a better understanding of the problem. With the requirements taxonomy the information is managed and classified into a single framework. The next step is then to use the available information to define and model the requirements, while assuring the traceability of the information. That challenge led to the formulation of the second research question:

Research Questions 2: How to combine the functions and systems hierarchies in the requirements mapping?

The function hierarchies are coming from both the operational and systems dimensions of the new design, while a generic system hierarchy can be defined to perform the desired functions. So how to assure the traceability between functional and system information during the definition of requirements?

Another important characteristic to account for during the requirements mapping is related to the information ambiguity and uncertainty. That observation led to the formulation of the third research question:

Research Questions 3: How to model subjective requirements?

In section 3.4, two types of uncertainty were discussed, the aleatory and epistemic uncertainties. The aleatory uncertainty is related to the natural variability of a physical phenomenon, while the epistemic uncertainty is caused by the lack of information or knowledge about the problem. This research focuses on the epistemic uncertainty.

It has been discussed in the requirements mapping section (3.3) of the literature review, that a structured mapping framework, like the QFD, can be used to reduce the epistemic uncertainty by guiding the design team through their decision process.

Based on the requirements mapping criteria established in section 3.3, the Analytic Network Process was selected as the common requirements mapping framework, and that statement represents the second hypothesis:

Hypothesis 2: The Analytic Network Process can be used as a common framework to map expectations, functions, systems, and resources.

The Analytic Network Process corresponds to the generalized case of the Analytic Hierarchy Process. Using this framework allows the mapping of the operational and systems elements, while assuring the traceability and providing a logical flow of information. Also, since ANP is based on ratio scale principles, both qualitative and quantitative information can be included in the decision model.

With respect to the uncertainty reduction, decomposing the problem into a hierarchical format reduces the number of comparisons per criteria. For instance, in the UAV experiment the maximum number of elements per criteria is 8, resulting in 28 pairwise comparisons. Consequently, the level of consistency between the comparisons can be expected to be better since the human brain channel capacity can only compare 7 ± 2 elements at the time [114]. Also, in ANP the comparison matrix properties allow the user to verify the consistency of the pairwise comparisons with the consistency index.

The ANP framework plays a major role in the development of the experiments of Chapter 5. In addition of providing a logical flow of information, ANP can be used to synthesize the relative importance of the elements included in the decision model. This feature of ANP is exploited to perform more detailed uncertainty analysis, which led to the next research question.

6.1.3 Revisiting Research Question 4 & Hypothesis 3

The fourth research question is also related to the second research objective and refers to fourth step of the proposed methodology. Even if the requirements mapping reduces the epistemic uncertainty by providing a structured framework, more information can be gained by analyzing the uncertainty surrounding the variability of the priorities resulting from the decision model synthesis. That challenge led to the formulation of the fourth research question:

Research Questions 4: How to assess and propagate the epistemic uncertainty in the requirements mapping?

This research questions implies that the uncertainty is propagated through the decision model framework. In Chapter 3, sensitivity analysis and Monte Carlo methods are discussed as uncertainty analysis techniques having the potential of being integrated with the requirements mapping. From this literature review the following hypothesis was formulated:

Hypothesis 3: Uncertainty analysis techniques integrated with the requirements mapping, combining both qualitative and quantitative information can be

used to reduce the epistemic uncertainty.

For the Presidential Helicopter experiment, both uncertainty techniques were applied to the decision model. The sensitivity analysis technique was considered not flexible enough to be integrated to the decision model, and the results not as intuitive to interpret as the Monte Carlo results. Therefore, only the Monte Carlo methods were utilized in the UAV experiment. For that experiment, the Monte Carlo methods were applied to determine the variability of the rankings, and also to analyze the results of the Benefits-Costs-Risks model. The knowledge acquired from these uncertainty analyses effectively reduced the epistemic uncertainty surrounding the down-selection of the systems alternatives.

6.1.4 Revisiting Research Question 5 and 6 & Hypothesis 4

The last research area refers to the down-selection of requirements while taking into account the available resources. The last two research questions were formulated to address the third research objective and correspond to the fifth and sixth steps of the proposed methodology. Since the operational and systems elements involve different comparison criteria, it becomes difficult to use that many criteria to down-select the top-level requirements. That observation led to the formulation of the fifth research question:

Research Questions 5: What are the down-selection criteria that can be used with the hierarchical model?

Also since the requirements are strongly related to the costs and resources associated with the project, the sixth research question was formulated as follows:

Research Questions 6: How to allocate resources to requirements in conceptual design?

In section 3.5, six criteria were established for the desired down-selection process. The down-selection process needed to be integrated to the decision model, while assuring the traceability in the flow of information and also being able to take into account both qualitative and quantitative information. From the literature review, the following hypothesis was formulated:

Hypothesis 4: A Benefits-Costs-Risks decision model can be combined with the requirements mapping and used for the down-selection and resource allocation.

The Benefits-Costs-Risks decision model is considered flexible enough to be applicable to a wide range of design projects. From the two experiments of Chapter 5, it has been found that most criteria can be regrouped under one of these categories.

For the Presidential helicopter experiment, the Benefits-Costs model was utilized to determine the economic, performance and social Benefits & Costs of selecting a specific shape configuration. During this experiment the Monte Carlo methods were also combined with the Benefits-Costs model to evaluate the potential integration of these two approaches to the ANP framework. The combination of both the Benefits-Costs model and Monte Carlo methods provided interesting information that could have been used to select the shape alternative of the vehicle.

For the UAV experiment, the Benefits-Costs-Risks model was implemented to map the systems MoEs with the systems alternatives. This BCR model utilized both qualitative and quantitative information gathered from the systems alternatives. Since multiple alternatives can be enumerated for a single system MoE, a matrix of alternatives and incompatibility matrix were created to explore the various system configurations. Following the exploration of the alternatives space, the Monte Carlo methods were applied to the BCR model in order to down-select the number of configurations, with the overarching goal in mind of determining the threshold and goal values for the requirements statement.

6.2 Summary of Research Contributions

The first contribution of this research is the creation of the proposed methodology. This methodology improves the understanding of the requirements by providing a structured framework to define and model the requirements. The proposed methodology allows the traceability of the information from the stakeholders expectations to the systems alternatives. It starts by using more qualitative information and ends by using more quantitative information from the systems alternatives.

The creation of the requirements taxonomy corresponds to the second contribution of

this thesis. This taxonomy can be used to help the design team to brainstorm the different project requirements and it can also be used to manage the information when applied in conjunction with a requirement management software like Telelogic DOORS.

The integration of ANP as a common framework to map the stakeholder expectations to the systems alternatives is the third major contribution of this research. This framework allows for the integration of uncertainty analysis like Monte Carlo methods and can also be used for the down-selection of system alternatives through a Benefits-Costs-Risks model. The integration of the morphological matrix with ANP and the Benefits-Costs-Risks model provided a unique and efficient way to compare large number systems configurations relatively rapidly.

Associated with the ANP framework, another contribution of this research is the process developed to synthesize multiple clusters of alternatives. Traditional ANP applications only use one cluster of alternatives, however in this research there were different clusters of alternatives associated with the different system MoEs, thus requiring the development of a new approach.

6.3 Recommendations for Future Research

Decision Model combined with Modeling and Simulation Environment:

Instead of using the quantitative information from historical data or previous design projects, the design team could take advantage of the availability of modeling and simulation environments to generate the desired quantitative information from physics-based models. It would be also interesting to investigate how the decision model evolves depending on the level of fidelity of the modeling environment.

Resource Allocation:

Since this research focuses on the development of the proposed methodology, only monetary resources were considered in both experiments of Chapter 5. It would be interesting to investigate how other resources like scheduling (time) and technology investments could be integrated to the model. Also, since the costs model was considered independent from the

decision mapping, future research could investigate how to integrate a parametric life cycle cost model. This model could be combined with the morphological matrix to determine the life cycle costs of all the compatible configurations, which could then be used within the BCR model.

Design Environment:

A more technical research task would be to create a computer based environment that would integrate the new ANP synthesis approach, and the Monte Carlo methods to the ANP framework. That environment could also allow the user to create a morphological matrix to automatically link the alternatives BCR model with the decision model. Furthermore, to provide better information management capability, the information could be mapped directly from the new ANP environment to a management software like DOORS.

Appendix A

REQUIREMENTS IDENTIFICATION TECHNIQUES

This chapter discusses common requirements elicitation methods from aerospace and systems engineering. Loucopoulos et Karakostas defined requirements elicitation as follows [107]:

“The process of acquiring (eliciting) all the relevant knowledge needed to produce a requirements model of a problem domain.”

In this research, it is assumed that some initial information is provided by the customer as a starting point. This information can take different forms depending on the type and magnitude of the project. It can be presented as a Request For Proposal (RFP), a mission statement, or even results from focus groups and customer surveys. In that perspective, the objectives of the requirements elicitation methods are described as follows:

- Gather the maximum amount of information about the systems and subsystems;
- Extract a large number of potential requirements;
- Manage requirements complexity.

The first two goals are self explanatory, however the third goal needs further explanation. In the context of complex system, managing requirements complexity implies having a structured methodology able to handle a large number of initial requirements, including conflicting requirements. It also means that the requirement elicitation process must be able to trace the impact of requirements from top-level systems to subsystems, which is called a top-down method. This chapter investigates two requirements elicitation methods, which are function analysis and systems architecture.

A.1 Function Analysis

Function analysis is used in many aerospace and systems engineering projects [49, 50, 85, 143]. It has the capability of decomposing complex systems into manageable components that can be described with functions. The International Council on Systems Engineering defined function as follows[82]:

“A function is a characteristic task, action, or activity that must be performed to achieve a desired outcome.”

Complex systems regroup large number of functions, and each of these functions provide information about the nature and the requirements of the system. Akiyama[5] provides a good definition of function analysis:

“Function analysis analyzes and identifies the nature of concepts as purposive actions involved in the creation of product and services.”

For a given system, these purposive actions are then organized into hierarchy of functions. The goal is to create a functional architecture capable of linking the requirements analysis with the design environment, as seen in Figure A.1. The functional architecture is then used as the basis of the system architectures (*Design Loop*), which will be described in section A.2. But first, the function analysis process is divided into three steps[5]:

1. Understand the object of analysis;
2. Define the functions;
3. Synthesize the functions.

A.1.1 Understand the Object of Analysis

The starting point to understand any given problem begins by collecting the available information. From the traditional systems engineering process (Figure A.1), the inputs represent the known information. This information can take the form of customer needs, system

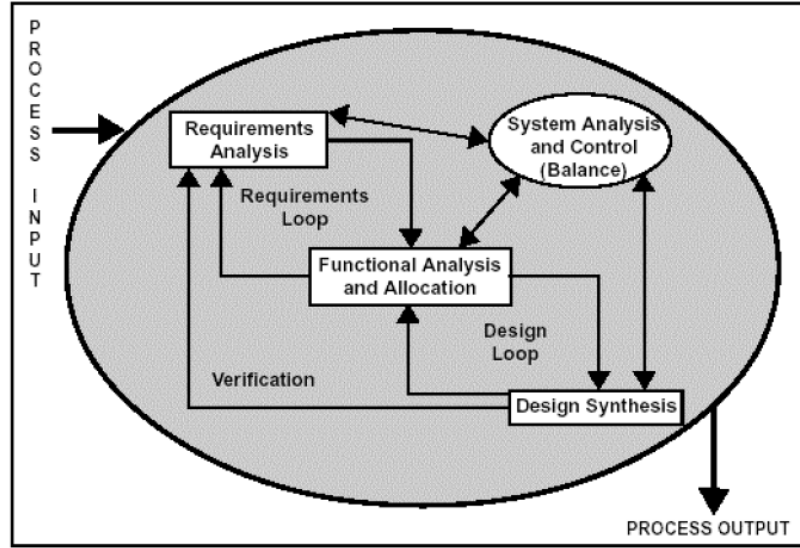


Figure A.1: Traditional Systems Engineering Process [43, 50]

objectives, RFP, technologies, standards, regulations, and even knowledge acquired from previous projects. Based on this initial amount of information, it is possible to identify top-level functions of the system. This step marks the beginning of the system decomposition, which can be qualified as a top-down approach. This implies that sub-functions are created based on top-level functions, and the process is repeated until no further function is created. Generally, there is a requirement assigned to every function, therefore there must be multiple iterations between function and requirements analyses. For every iteration, new information (function and requirement) is identified, and every new piece of information leads toward a better understanding of the system. With this framework in mind, the next activity consists of defining the functions.

A.1.2 Define the Functions

The functions are defined by asking the question: “*what is the task, action or activity performed?*” The function expression is composed of a verb followed by a noun. Ideally, the definition must be as simple as possible, using specific language to eliminate any misunderstanding. Furthermore, the words chosen for the definition must not be related to the function being performed. This characteristic is important so that the creativity of the design team is not biased by any potential concept. Table A.1 presents examples of function

expressions.

Table A.1: Examples of Function Expressions

System of Function Definition	Proper Expression	Improper Expression
Wing	Create lift	Sustain aircraft weight in the air
Engine	Generate torque	Generate thrust
Fuselage	Provide payload accommodation	Provide passenger accommodation

It can be seen that improper expressions are often too specific. For instance the engine thrust implies turbojet or turbofan engines, however similar engine can be mounted on fixed or rotary wing aircraft. Generating thrust for a rotary wing aircraft does not make sense, on the other hand generating torque can be applied to both types of aircraft. Once all the functions of the systems have been identified, the remaining effort consists of synthesizing the functions.

A.1.3 Synthesize the Functions

The main goal of the synthesis process is to create a hierarchy of functions, so that the top-level functions are logically decomposed into sub-functions. At this point, one may wonder, when to stop the decomposition process? Depending on the overall system complexity, it can be argued that elementary functions need to be reached. However this might require too much effort and resources. It is important to remember that this process is iterative, consequently as requirements are emerging, new functions are added to the hierarchy. In addition to the hierarchy itself, the synthesis process identifies the individual functional interfaces (inputs and outputs) for every function. Existing tools such as Functional Flow Diagram (FFD) (Figure A.2), and N² chart (Figure A.3) are used to assist the design engineer through this task.

As it can be seen from Figure A.2, the functional flow diagram represents the functional decomposition. Each box includes a function, and the user must supplement a list of inputs and outputs (interfaces) for each function. Sometimes a function can be decomposed in more than one function. In this case the user indicates if one function (*OR*) or more than one

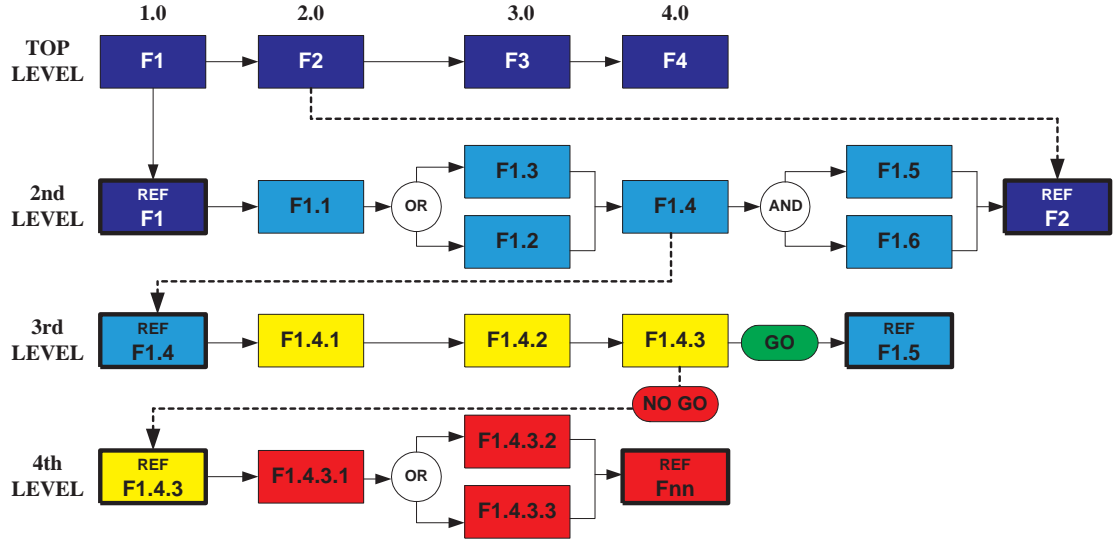


Figure A.2: Generic Functional Flow Diagram [82]

function (AND) is needed to complete the decomposition. Also, GO and NO-GO sequences are used for conditional event.

While the functional flow diagram is multi-level and provides information about the functional decomposition, the N^2 chart describes the functional interfaces. Figure A.3 shows a generic example of an N^2 chart. The functions are positioned on the main diagonal, while the interfaces are filling the lower and upper triangular parts of the chart. This tool enables the analysis of functional and physical interfaces, while being able to indicate potential conflicts.

Function analysis is an excellent method to decompose a problem or system into smaller and more manageable components. It also provides visual aids representing relationships between functions and functional interfaces. However, for complex systems it may require a significant amount of time and effort to generate the final functional architecture. Furthermore, it is difficult to define a clear criteria to stop the decomposition process. The solution for these problems is to iterate between requirements, functional architecture and system architecture. By doing so, every new piece of information is used to create new requirements, functions and systems. The next section describes the systems architecture, which is based on the functional architecture.

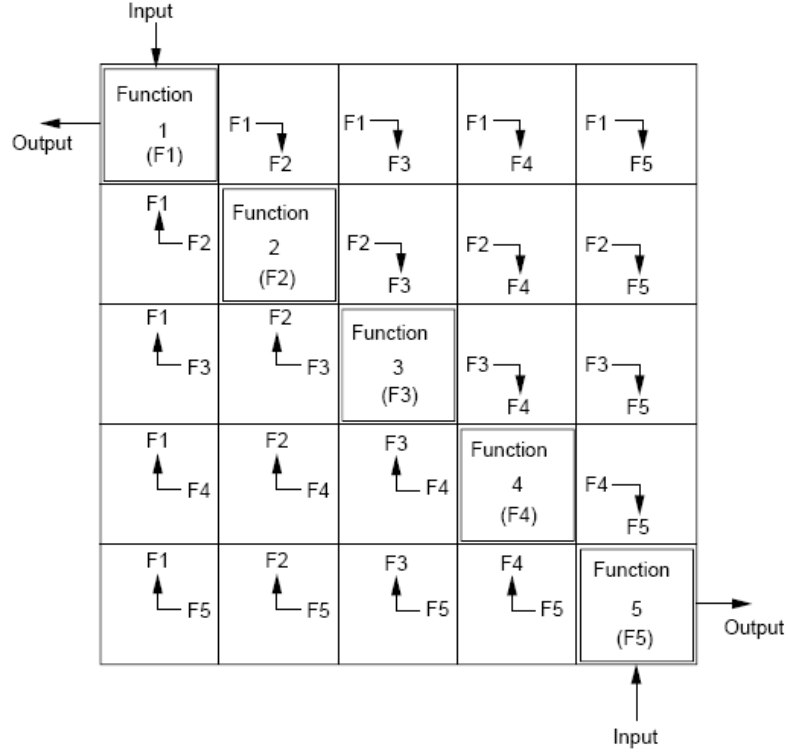


Figure A.3: N^2 Chart Generic Example [82]

A.2 System Architecture

“The success or failure of many civil and defense systems depends mainly on their architecture”[146]. System architecture is one of the first step of the synthesis process. The synthesis process consists of “bringing together” all the information acquired in requirements and function analyses. This knowledge is then converted into physical concepts, which are organized in system architectures. Figure A.4 depicts the system architecture synthesis process as defined by INCOSE[82].

The process starts with an iteration loop between system elements and system architectures. An example of aircraft system architecture is presented in Figure A.5. As for the functional architecture, there are multiple levels of system elements. The aircraft system is first divided into top-level systems present in the life cycle of the aircraft, such as training and support. Afterward, the aircraft is further decomposed into subsystems. There is no optimal way of synthesizing all these components into system architectures. [146]. However the system architecture must be able to perform all the functions defined in the functional

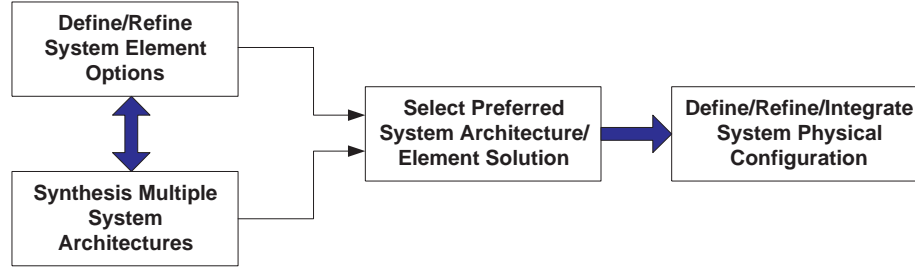


Figure A.4: System Architecture Synthesis [82]

architecture. It is important to note that even though the functional and system architectures are closely related, the system architecture has greater potential of changing during the design process than the functional architecture. The reason is relatively simple, for every function there are multiple alternatives or systems that can be used to perform the related task or action. The next step shown in Figure A.4 is to select a preferred system architecture, which will lead to the system physical configuration.

As a reminder, the main objective of this thesis is to create a methodology that enables the identification, definition and selection of a critical set of requirements. In that perspective, system and function architectures are used to generate an initial set of requirements (identification and definition), and not to select a specific and precise physical configuration. However, the system architecture must include enough detail to decompose the complex systems into manageable systems and subsystems. For instance, the “*Wing*” within the airframe segment (9.8) in Figure A.5 is still a general system definition, since it does not specify the wing planform shape, type of airfoil or its location with respect to the fuselage. In order to create relationships between requirement models and system models, the wing can be parametrically defined with physical variables such as span, chord and aspect ratio. These relationships can then be regrouped into the Quality Function Deployment process for further analysis.

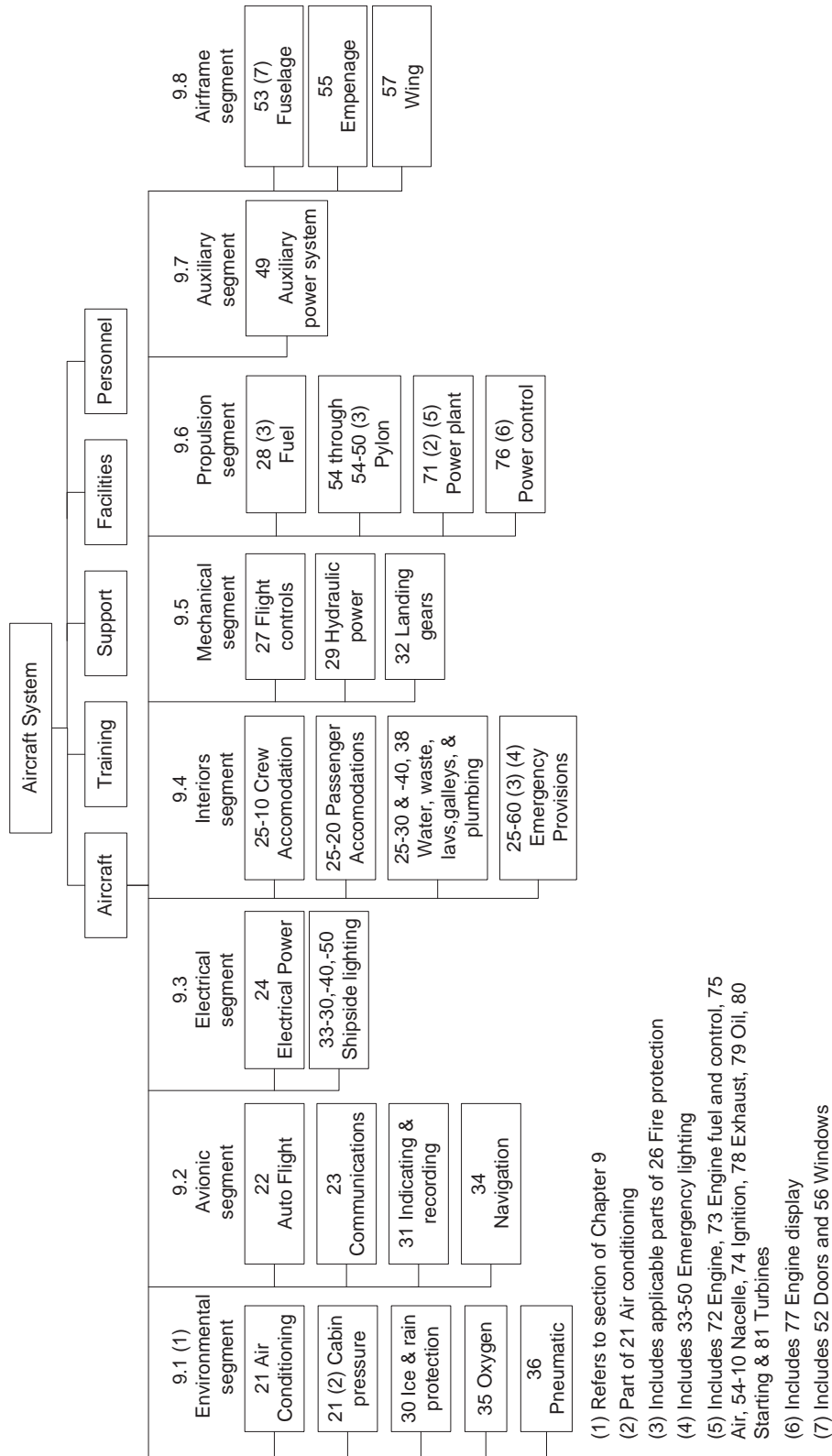


Figure A.5: Aircraft System Architecture [85]

Appendix B

INTRODUCTION TO FUZZY SET THEORY

Fuzzy sets were introduced by Lotfi Zadeh in 1965 [202]. He was interested in defining classes of objects that were not precise, such as the class of “tall man”, which is different than the precisely defined class of man being 6 feet tall. Fuzzy set theory is based on the concepts of imprecision and uncertainty. In fact, the main objective is to accept the imprecision and uncertainty in order to better understand the object of analysis. This section is divided in two parts; first an introduction to fuzzy set theory, and second the difference between fuzzy set theory and probability theory.

B.0.1 Introduction to Fuzzy Set Theory

Many books introduce the concept of fuzzy set theory by comparing it with classical, crisp, set theory [94, 93, 151, 206]. The purpose of this comparison is to differentiate the concept of precision (crisp) and imprecision (fuzzy), as illustrated in Figure B.1. In this figure, the “Universe of discourse” defines all the available information for a given problem [Ross, 2004]. The boundary of the classical set theory is precise, either the element is a member or not a member of the set. In contrast, the boundary of the fuzzy set is imprecise, the element can be included, excluded or within the boundary. In other words, fuzzy set allows variable degrees of membership through the boundary. In classical set theory, the membership of an element is either 1 (included) or 0 (excluded). However in fuzzy set theory and more specifically within the boundary, the membership value is varying from 1 at the inside edge of the boundary to 0 at the outside edge. Membership function is an important concept of fuzzy set theory, it is described in more detail in section B.0.3.

Another fundamental aspect of fuzzy set theory is the notion of uncertainty. Klir et al defines uncertainty as follows [93]:

“Uncertainty is the condition in which the possibility of error exists, because we

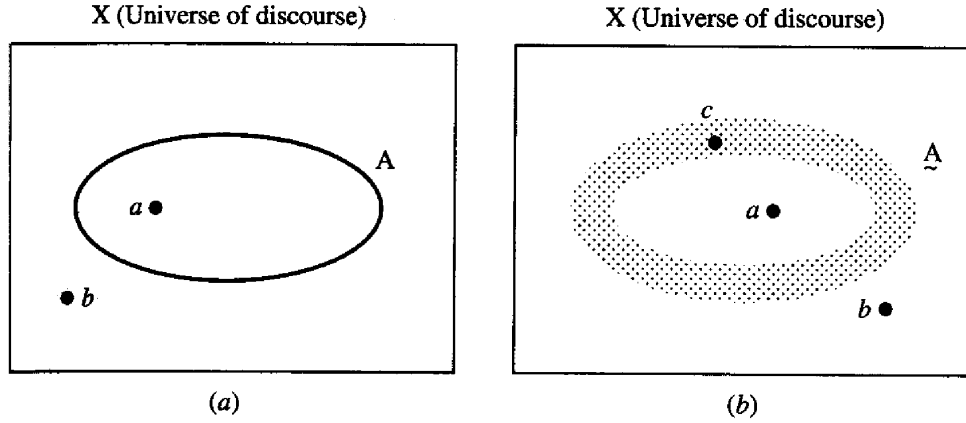


Figure B.1: Classical Set (a) vs. Fuzzy Set (b) [151]

have less than total information about our environment.”

From the start, fuzzy set theory assumes that the problem is uncertain. There are different types of uncertainty, which can be categorized as follows[151]:

- **Fuzzy:** not sharp, unclear, imprecise or approximate;
- **Vague:** not specific or amorphous;
- **Ambiguous:** too many choices or contradictory choices;
- **Form of ignorance:** dissonant or not knowing something;
- **Natural variability:** conflicting, random, chaotic or unpredictable.

The example of a delivery person that has to travel to locations A, B, C and D can be used to illustrate these concepts of uncertainty. The distances between these locations are precisely known, and can be regrouped in a crisp set, $D = \{d_{ab}, d_{ac}, d_{ad}, d_{bc}, d_{bd}, d_{cd}\}$. Following the classical theory, one can evaluate the time to travel between these locations by assuming a given average speed, and dividing the distance by the speed. However, in reality the time to travel is highly uncertain. It can depend on traffic (natural variability), the choice of path (ambiguous), the number of stops and traffic lights (vague), and the actual speed at

which the vehicle is traveling (fuzzy). At this point, one could suggest to add a probabilistic distribution on the time to travel in order to take into account the uncertainty, which bring the following question: what is the difference between fuzzy set theory and probability theory?

B.0.2 Fuzzy Set Theory and Probability Theory

The difference between fuzzy set theory and probability theory lies in the type of uncertainty they represent. Probability theory deals with random uncertainty, the chance or frequency at which an event will occur. On the other hand, fuzzy set theory represents imprecise and approximate uncertainty. It describes how well the concept of analysis matches its true meaning. A good example to illustrate the fundamental difference between fuzzy set theory and probability theory, is the thirsty traveler example [17].

After a really long journey, the thirsty traveler is placed in front of two bottles of “potable water”, and he must only drink one of them. He is told that bottle #1 is filled with water that has 97% chance of being potable, while bottle #2 has a membership of 0.97 in the class of potable water. Which bottle should he drink? Since the traveler is a well educated man, he knows that even though bottle #1 has 97% chance of being potable, there is still 3% chance of having pure poison in the bottle. Knowing that a membership value of 1 corresponds to pure potable water, this implies that bottle #2 resembles to pure potable water with a membership value of 0.97. It is now apparent with this example that both theories are representing different type of information. While probability theory deals with event frequency and chance, fuzzy set theory deals with imprecision and vagueness. Depending on the problem, fuzzy set theory and probability theory can be combined to provide even more information to scientists and engineers.

B.0.3 Membership Function

Membership function is one of the most important concept of fuzzy set theory. Figure B.2 shows a trapezoidal and triangular membership functions. The level of membership corresponds to the y axis, and it varies between 0 and 1. The concept that needs to be modeled, universe of discourse, is on the x axis. Depending on the type of problem, membership

functions can take different forms, the most commonly used are triangular, trapezoidal and bell curve. A membership function is defined by its core, support and boundaries. The core corresponds to a membership value of $\mu(x) = 1$. The support is the region where the membership value is greater than zero, $\mu(x) > 0$, and the boundaries are defined by membership values between 0 and 1, $0 < \mu(x) < 1$. In Figure B.2, there is an example of membership function for computational time. The user divides the Universe of discourse ($Time(s)$) in three regions, Short, Acceptable and Long computational time. In this case, intuition is used to generate the membership function. This section describes different approaches to define membership functions (fuzzification), and techniques to convert membership function into scalar value (defuzzification). The application of these processes is demonstrated in the Fuzzy Quality Function Deployment method. FQFD is an important concept, since it is utilized in the proposed methodology.

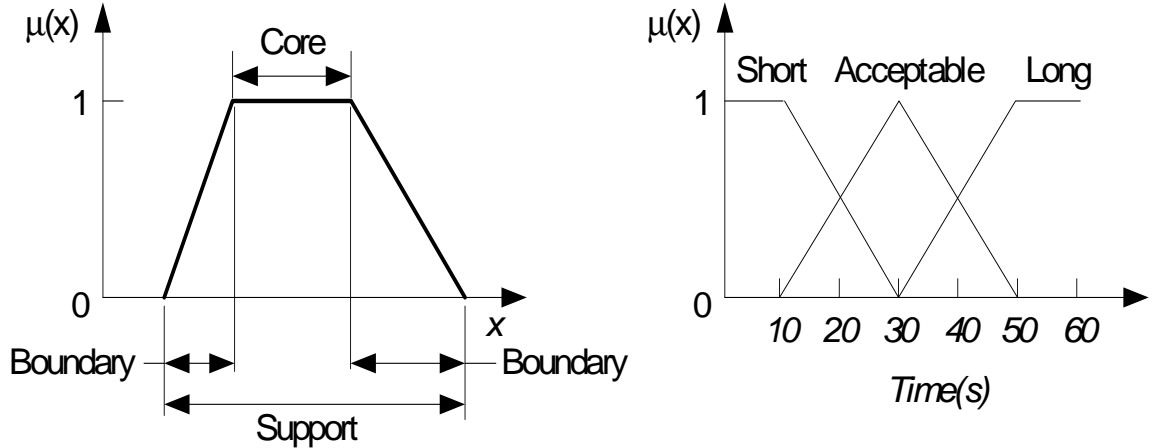


Figure B.2: Definition of Membership Function[151]

B.0.3.1 Fuzzification Process

Fuzzification is the process of translating a crisp set of data into a fuzzy set. This section describes approaches used in the literature to define membership functions [47, 90, 151, 169]:

1. Intuition;
2. Inference;
3. Rank ordering;

4. Neural networks;
5. Genetic algorithms;
6. Inductive reasoning.

Note that all of these methods are described in detail in reference [151]. The goal here is to summarize the different techniques, and to identify their potential application in the proposed methodology. The first three approaches (a, b, c) are relatively simple. They are generally used as initial guesses, when little information is known about the problem. As its name suggests, the intuition approach is based on the current knowledge of the user. In this case, it is important to notice the number of curves, their location in the universe of discourse, and where the curves are overlapping. These characteristics provide information about the assumptions of the user. The inference approach utilizes existing knowledge to infer rules or conclusions about the shape of the membership function. The rank ordering method involves surveys, polls or focus groups to define preferences, and to compare different alternatives. The membership values are then defined by ordering the preferences in the universe of discourse.

The last three approaches (d, e, f) are more advanced, and they are used when information is available through data sets. Neural network tries to mimic the behavior of neuron in the human brain[14, 37, 38, 161]. It is used for modeling purposes because it has the capability to adapt and learn while new elements are added to the data set. The process of generating membership function with neural network is illustrated in Figure B.3 [Takagi and Hayashi, 1991]. The first step consists of dividing the data set into a training and a reference sets. The training data set “teaches” the neural network to classify the data within three regions (R^1 , R^2 and R^3) (Figs.B.3a, b, c). The reference data set is then used to calculate the error between the predicted values of the neural network and the actual reference values, (Figs.B.3d, e, f). Once the error is deemed acceptable, the neural network is used to evaluate membership value for other data sets (Figs.B.3g, h, i).

Genetic Algorithm is an approach that mimics the natural selection process. It follows Darwin’s theory of evolution and more specifically the “survival of the fittest” , meaning that

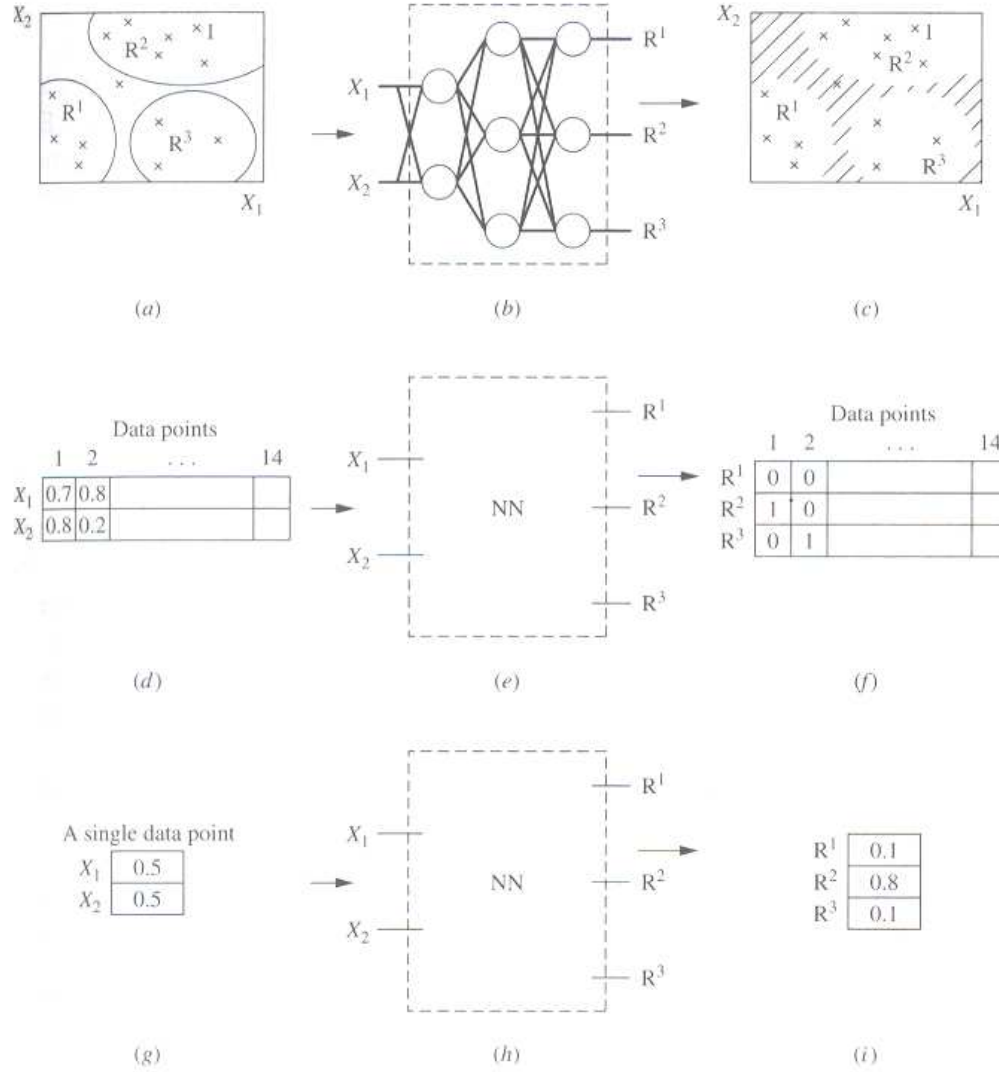


Figure B.3: Define Membership Function with Neural-Network [169]

only the fittest organisms survive the reproduction, crossover and mutation processes [53, 52]. These processes are translated into algorithms that have the capability of searching for optimal solutions in large design space. For this research, the optimal solution corresponds to the shape of the membership function [90]. The process of defining the shape of the membership function using genetic algorithm is illustrated in Figure B.4. A simple data set including one independent variable (x) and one dependent variable (y) is used as an example. Functional relationships are then established and translated as initial guesses for the membership functions. In this case, the bases of the triangular membership functions are the variables used in the optimization process. These bases are then translated into

binary strings, and the initial genetic algorithm population is created. Consequently, the final results of the genetic algorithm optimization will provide bases values that will match the data set and the functional relationships.

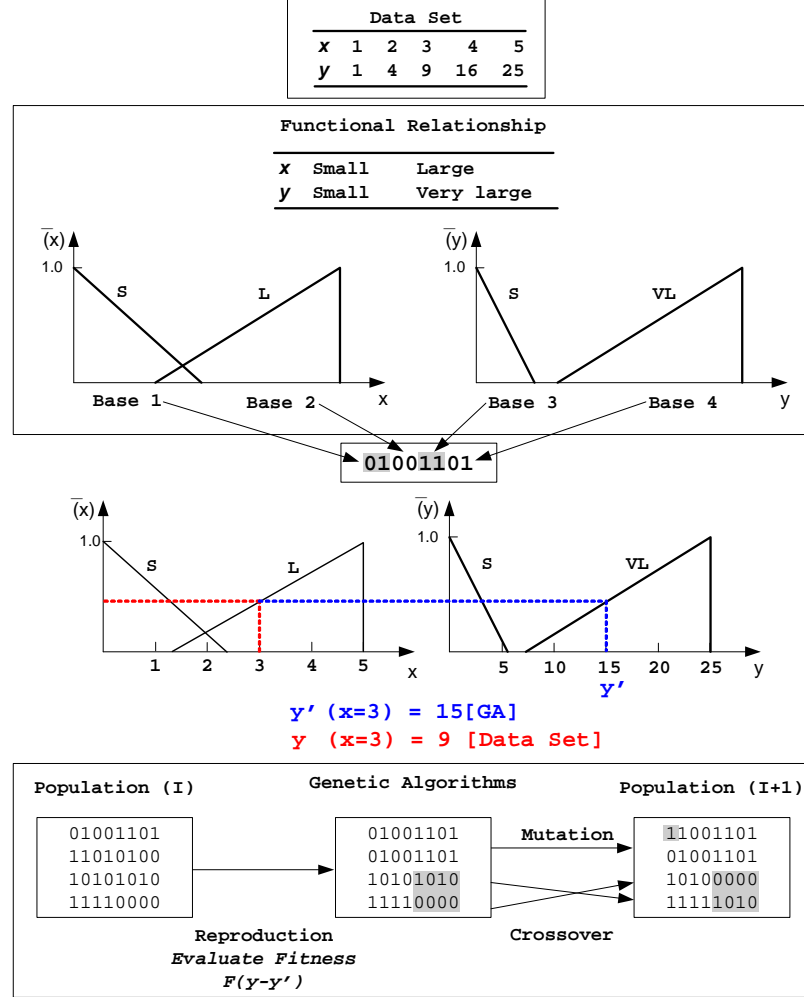


Figure B.4: Define Membership Function using Genetic Algorithms[151, 52]

The inductive reasoning approach can also be used to determine membership function from data set. This method is based on the entropy minimization principle first described by De Luca and Termini [1972] [42]. In this context, the entropy is a representation of the uncertainty distribution. The objective is then to create a membership function that minimizes the entropy[197]. The generation of membership function using inductive reasoning can be done following Christensen's approach [30]. This method is not described in great detail in this document, because it is only applicable to static data sets[151]. This is a

serious limitation for the current research, since the behavior of the customer is inherently dynamic, which translates into dynamic data sets. For this reason, neural network and genetic algorithms are deemed more applicable in the context of the proposed methodology.

The previous approaches described how to create membership functions from crisp sets of data. The following section will describe the opposite process, how to extract a precise value from a membership function.

B.0.3.2 Defuzzification

Defuzzification is the process of converting a fuzzy membership function into a scalar value. For instance, some legacy codes and mathematical models have been constructed in such way that only scalar values can be used as inputs. If the inputs include fuzzy numbers, the user must find a way to translate the fuzzy membership function into a scalar value, while minimizing the loss of information.

There are many defuzzification approaches available in the literature[68, 67, 153, 154, 184]. This section describes the most common techniques as presented by Ross (2004). The figures and equations in Table B.1 are adapted from reference [151]. The defuzzification techniques depicted in this table are: max membership principle, centroid method, weighted average method, mean max membership, center of sums, and center of largest area.

In Table B.1, $\mu_{\tilde{C}}(z)$ represents the fuzzy membership function, which is related to the fuzzy concept z . The variable, \bar{z} , represents the centroid of symmetric membership function. The defuzzification process attempts to capture the behavior of the membership function with a single scalar, z^* . The variety of techniques suggests that the defuzzification process is problem dependent. One of the sub-objectives of the proposed methodology is then to investigate the impact of the selected defuzzification technique on the requirements analysis

The next section presents the application of fuzzification and defuzzification techniques through fuzzy quality function deployment. The FQFD method is important since it constitutes an integral part of the requirements modeling process.

Table B.1: Defuzzification Techniques [151]

Name	Equation	Graphical representation
Max membership principle	$\mu_{\tilde{C}}(z^*) \geq \mu_{\tilde{C}}(z) \quad (\text{B.1})$ <p>for all $z \in Z$</p>	
Centroid method	$z^* = \frac{\int \mu_{\tilde{C}}(z) \cdot z dz}{\int \mu_{\tilde{C}}(z) dz} \quad (\text{B.2})$	
Weighted average method	$z^* = \frac{\sum \mu_{\tilde{C}}(\bar{z}) \cdot \bar{z} dz}{\sum \mu_{\tilde{C}}(\bar{z}) dz} \quad (\text{B.3})$	
Mean max membership	$z^* = \frac{a + b}{2} \quad (\text{B.4})$	
Center of sums	$z^* = \frac{\int_Z \bar{z} \sum \mu_{\tilde{C}}(z) dz}{\int_Z \sum \mu_{\tilde{C}}(z) dz} \quad (\text{B.5})$	
Center of largest area	$z^* = \frac{\int \mu_{\tilde{C}_m}(z) \cdot z dz}{\int \mu_{\tilde{C}_m}(z) dz} \quad (\text{B.6})$	

B.0.4 Fuzzy Quality Function Deployment

The fundamental goal of FQFD is the same as for the traditional QFD, which is to relate customer requirements with engineering characteristics. As observed in section 3.3.2, the traditional QFD process has some limitations regarding the modeling of uncertainty, and the choice of scale used for relationships and correlations matrices. In order to overcome these limitations, the FQFD process has been developed, and it continues to be an active area of research today[173, 190, 187, 55, 171, 29, 104]. This section illustrates the role of fuzzification and defuzzification in the FQFD methodology.

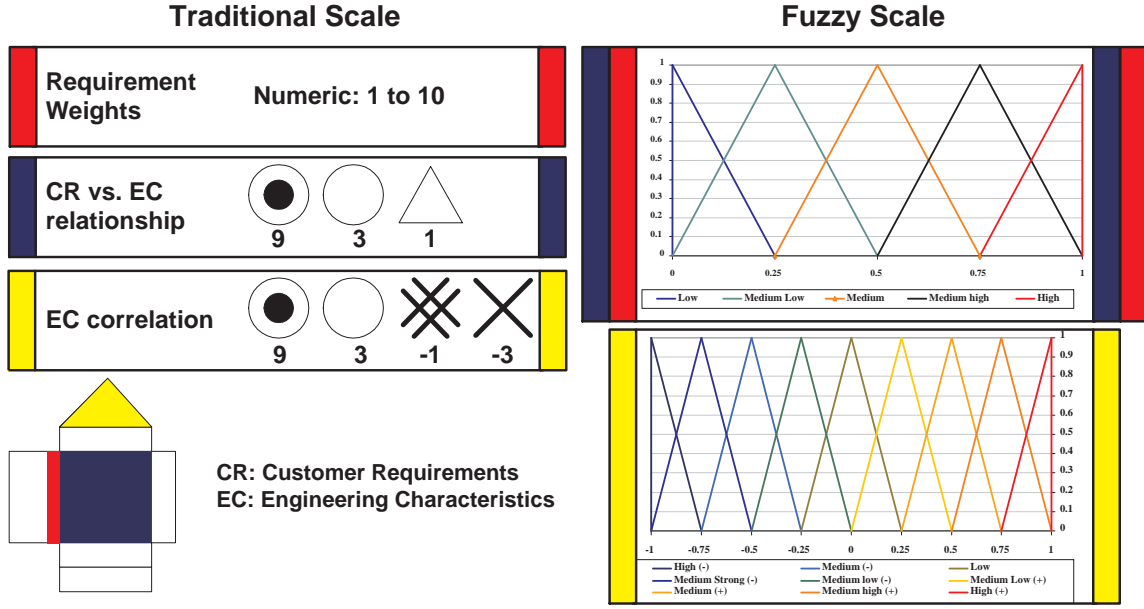


Figure B.5: FQFD Scales

One of the main results of the FQFD process is the ranking of the Engineering Characteristics. Traditionally, to obtain this ranking the design team starts by assigning a weight for each Customer Requirement. The next step consists of filling the relationship matrix using a non-linear scale, usually $\{0, 1, 3, 9\}$. The relative importance of engineering characteristic with respect to customer requirement is calculated as follows:

$$ECr_j = \frac{\sum_{i=1}^n W_i R_{ij}}{\sum_{i=1}^n W_i}, \quad j = 1, \dots, m \quad (\text{B.7})$$

where ECr_j is the relative importance of the EC (j), W_i is the weight of the CR (i), and R_{ij} is the relationship between CR (i) and EC (j). The ranking is done for m engineering characteristics and n customer requirements. It is important to note that the traditional approach does not take into account the EC correlations, “roof of the house”. Figure B.5 illustrates the difference of scales between the traditional and fuzzy QFD methods. In this figure the fuzzification process is achieved by using triangular membership functions, however depending on the problem other types of membership function could be used.

It can be observed from Figure B.5, that the same fuzzy scale is utilized for CR weights, and CR vs. EC relationships. It is important to reiterate that these membership functions

constitute an initial guess, as more information is acquired, the shape of the membership functions will change. The calculation of the EC relative importance in the FQFD approach is not as simple as in equation B.7. Crisp numbers are now replaced by fuzzy membership functions. Consequently, it requires fuzzy weighted averaging techniques to calculate the relative importance of the EC. The general equation to calculate fuzzy weighted average is described as follows [104]:

$$\widetilde{ECr_j} = \frac{\sum_{i=1}^n \tilde{W}_i \tilde{R}_{ij}^*}{\sum_{i=1}^n \tilde{W}_i}, \quad j = 1, \dots, m \quad (\text{B.8})$$

The symbol (\sim) indicates that the variable is a fuzzy number. \tilde{R}_{ij}^* represents the fuzzy relationship number between the CR and EC. The (*) implies that the relationship includes the impacts of the EC correlation matrix, which is depicted as follows [55, 171]:

$$\tilde{R}_{ij}^* = \sum_{k=1}^m \tilde{R}_{ik} C_{kj} \quad (\text{B.9})$$

where C is the engineering characteristic correlations matrix. There exist many different techniques to calculate fuzzy weighted average [99, 89, 186]. The approach depicted below has been proposed by Kao and Liu (2001). It is based on α -cuts (or λ -cuts, depending on the reference) representation of membership function, as illustrated in Figure B.6.

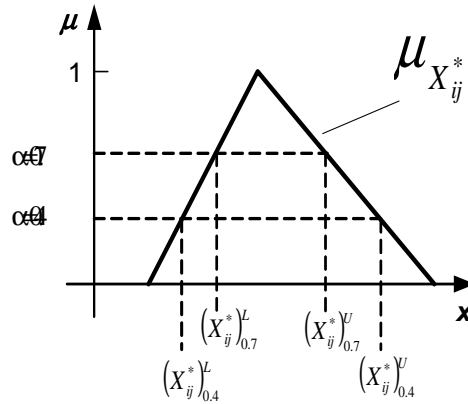


Figure B.6: α -cuts Representation of Membership Function

The α -cuts technique can be viewed as a defuzzification process, since every cut intersects the membership function at two locations, $\left(X_{ij}^*\right)_{\alpha}^L$ and $\left(X_{ij}^*\right)_{\alpha}^U$. Therefore to calculate the

EC relative importance membership function, $\mu_{\tilde{ECr}_i}$, one must solve the following systems of equations[89]:

$$\begin{aligned} (ECr_j)_\alpha^U &= \max \left(\frac{\sum_{i=1}^n w_i x_{ij}^*}{\sum_{i=1}^n w_i} \right) \\ \text{s.t. } (W_i)_\alpha^L &\leq w_i \leq (W_i)_\alpha^U, \quad i = 1, \dots, n, \\ (X_{ij}^*)_\alpha^L &\leq x_{ij}^* \leq (X_{ij}^*)_\alpha^U, \quad i = 1, \dots, n, \quad j = 1, \dots, m \end{aligned} \quad (\text{B.10})$$

$$\begin{aligned} (ECr_j)_\alpha^L &= \min \left(\frac{\sum_{i=1}^n w_i x_{ij}^*}{\sum_{i=1}^n w_i} \right) \\ \text{s.t. } (W_i)_\alpha^L &\leq w_i \leq (W_i)_\alpha^U, \quad i = 1, \dots, n, \\ (X_{ij}^*)_\alpha^L &\leq x_{ij}^* \leq (X_{ij}^*)_\alpha^U, \quad i = 1, \dots, n, \quad j = 1, \dots, m \end{aligned} \quad (\text{B.11})$$

It is important to note that the variables in equations B.10 and B.11 are not fuzzy numbers. They are scalars because they correspond to specific α -cut. Kao and Liu (2001) demonstrated the nonlinear behavior of the fuzzy weighted average membership function. Consequently, these equations are generally resolved numerically, since most cases do not have an analytical solution. Figure B.7 shows an example of fuzzy weighted average membership functions. The final step is then to apply defuzzification techniques to the membership functions in order to rank the engineering characteristics.

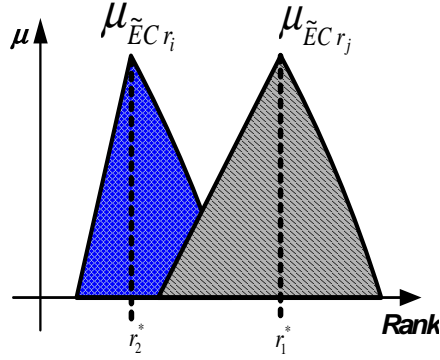


Figure B.7: Results of Fuzzy Weighted Average

Section B.0.3 introduced methods that are currently used to define membership functions either based on customer inputs or data sets. More specifically, different fuzzification and defuzzification approaches were described, and their applicability was demonstrated through the FQFD method.

Appendix C

PRESIDENTIAL HELICOPTER SURVEY

This survey was given to 46 graduate students enrolled in the course AE 8804 Advanced Design Methods 1.

Consent Disclaimer

The participant has consented the Georgia Institute of Technology Department of Aerospace Engineering to release the results of this survey to Stephane Dufresne in connection with the dissertation of Stephane Dufresne. Georgia Institute of Technology assumes no liability whatsoever, for the contents which arises in connection with or as a result of this survey. By completing the survey I acknowledge receipt of this consent. Thanks you.

Evaluation of Subjective Requirements

Background:

The presidential helicopter, Marine One, is one of the most photographed helicopters in the world. In 2005, a multi billion dollar contract was awarded to renew the fleet of Presidential Helicopters. One of the requirements included in the request for proposal was that the new design should look "presidential".

Requirement [R1]:

The helicopter should look presidential.

Objective of the Questionnaire:

1. Define the "presidentiality" elements of the helicopter.
2. Estimate the importance of the elements and sub-elements on the requirement R1.

Assumptions:

It is assumed that the following elements influenced the "presidentiality" appearance of the helicopter



Directions:

While doing a pairwise comparison of the different concepts, please circle your preference regarding the "presidentiality" of the concept. Note, you can circle up to 2 adjacent attributes.

Car example:

QUESTION

Which vehicle of the pairwise comparison looks more "sporty"?

Please circle your preference:

Comparison → OR

The answer should be read as follows:

The **Corvette** is **more sporty** than the **Camry**.

<http://www.toyota.com/>

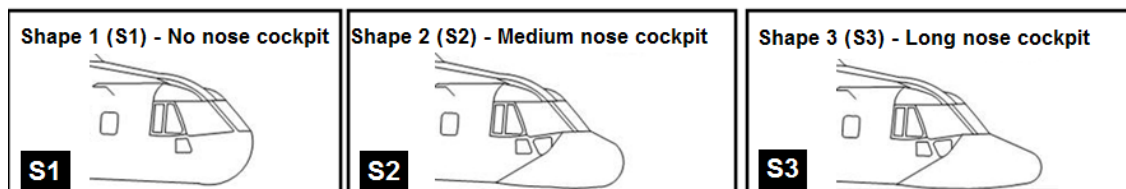


<http://www.chevrolet.com>



PART 1

Determine if the shape has an impact on the "presidentiality" of the helicopter. Here are the different shapes considered:



QUESTION 1 - COCKPIT:

Do you think that the cockpit nose shape has an impact on the "presidentiality" attribute of the vehicle?

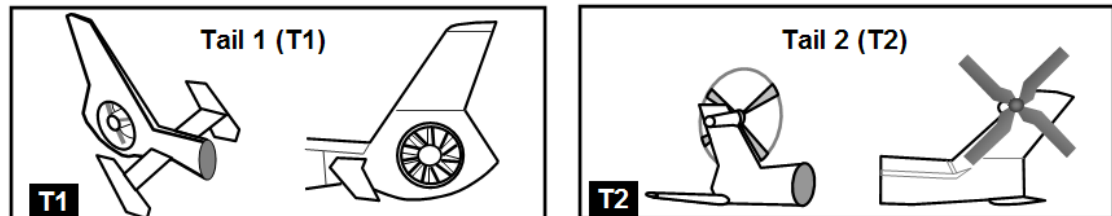
YES NO

If YES, please circle your preference:

Concept _____ looks more "presidential" than Concept _____

- a) S1 OR S2
- b) S1 OR S3
- c) S2 OR S3

QUESTION 2 - TAIL ROTOR:



Do you think that the tail assembly shape has an impact on the "presidentiality" attribute of the vehicle?

YES NO

If YES, please circle your preference:

Concept _____ looks more "presidential" than Concept _____

- a) T1 OR T2

QUESTION 3 - OTHER SHAPES:

Do you think that any other external shapes could provide a "presidentiality" aspect to the vehicle?

QUESTION 4 - RANK SHAPES:

Rank the different shapes, where (1) is the more presidential.

Please add the elements of QUESTION 3 to the ranking.

RANK	SHAPE
	Cockpit
	Tail







PART 2

Determine if the aesthetics has an impact on the "presidentiality" of the helicopter. Here are the different colors, paint schemes and stickers considered:

QUESTION 5 - PRIMARY COLOR:

Do you think that the primary color has an impact on the "presidentiality" attribute of the vehicle?

YES NO

Blue		Black	
Brown		Green	
Grey		Red	

If YES, please circle your preference between the different options:

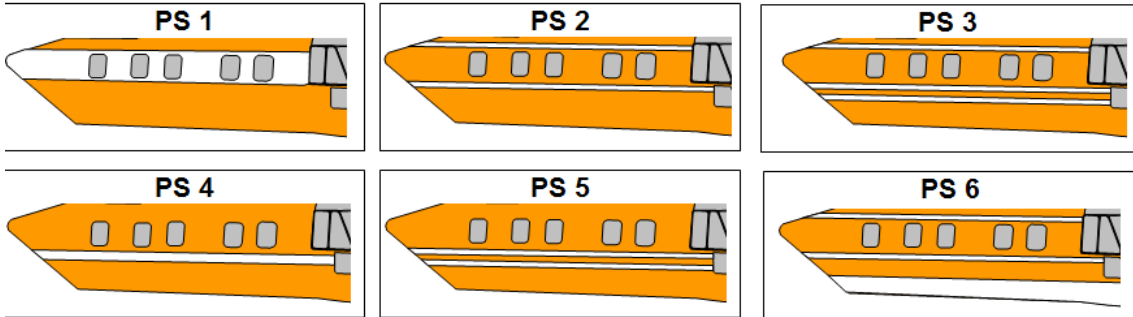
- | | | | | | |
|----------|----|-------|----------|----|-------|
| a) Blue | OR | Brown | j) Grey | OR | Black |
| b) Blue | OR | Grey | k) Grey | OR | Green |
| c) Blue | OR | Black | l) Grey | OR | Red |
| d) Blue | OR | Green | m) Black | OR | Green |
| e) Blue | OR | Red | n) Black | OR | Red |
| f) Brown | OR | Grey | o) Green | OR | Red |
| g) Brown | OR | Black | | | |
| h) Brown | OR | Green | | | |
| i) Brown | OR | Red | | | |

QUESTION 6 - PAINT SCHEME:

Do you think that paint schemes have an impact on the "presidentiality" attribute of the vehicle?

YES NO

If YES, please circle your preference:

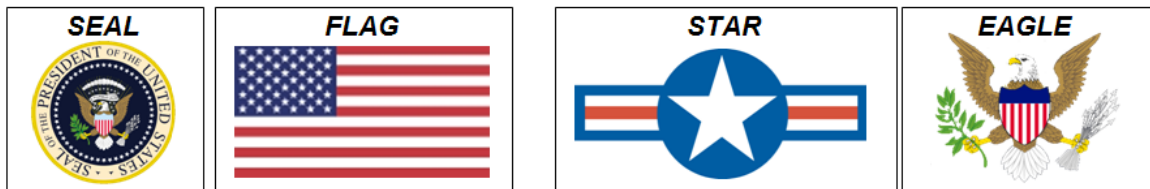


- | | | | | | |
|---------|----|------|---------|----|------|
| a) PS 1 | OR | PS 2 | j) PS 3 | OR | PS 4 |
| b) PS 1 | OR | PS 3 | k) PS 3 | OR | PS 5 |
| c) PS 1 | OR | PS 4 | l) PS 3 | OR | PS 6 |
| d) PS 1 | OR | PS 5 | m) PS 4 | OR | PS 5 |
| e) PS 1 | OR | PS 6 | n) PS 4 | OR | PS 6 |
| f) PS 2 | OR | PS 3 | o) PS 5 | OR | PS 6 |
| g) PS 2 | OR | PS 4 | | | |
| h) PS 2 | OR | PS 5 | | | |
| i) PS 2 | OR | PS 6 | | | |

QUESTION 7 - STICKERS:

Do you think that stickers have an impact on the "presidentiality" attribute of the vehicle?

YES NO



COUNTRY
UNITED STATES OF AMERICA

If YES, please circle your preference:

- | | | | | | |
|---------|----|---------|----------|----|---------|
| a) SEAL | OR | FLAG | f) FLAG | OR | EAGLE |
| b) SEAL | OR | STAR | g) FLAG | OR | COUNTRY |
| c) SEAL | OR | EAGLE | h) STAR | OR | EAGLE |
| d) SEAL | OR | COUNTRY | i) STAR | OR | COUNTRY |
| e) FLAG | OR | STAR | j) EAGLE | OR | COUNTRY |

QUESTION 8 - OTHER AESTHETICS:

Do you think that any other aesthetics properties could provide a "presidentiality" aspect to the vehicle?

_____	_____	_____
_____	_____	_____
_____	_____	_____

QUESTION 9 - RANK AESTHETICS:

Rank the different aesthetics characteristics, where (1) is the most presidential one.

Please add the elements of QUESTION 7 to the ranking.

RANK	AESTHETICS
	Color
	Paint scheme
	Stickers

PART 3

Determine if the departure and arrival protocols have an impact on the "presidentiality" of the helicopter.
Here are the different protocols considered:

Guards standing by the helicopter doors



Red carpet for arrival and departure



QUESTION 10 - PROTOCOLS:

Do you think that protocols have an impact on the "presidentiality" attribute of the vehicle?

YES NO

If YES, please circle your preference:

QUESTION 11 - OTHER PROTOCOLS:

Do you think that any other protocols could provide a "presidentiality" aspect to the vehicle?

_____	_____	_____
_____	_____	_____
_____	_____	_____

QUESTION 12 - RANK PROTOCOLS:

Rank the different protocols, where (1) is the most presidential one.

Please add the elements of QUESTION 10 to the ranking.

RANK	AESTHETICS
	Guards
	Red Carpet

QUESTION 13 - COMPARE ELEMENTS IMPORTANCE:

After having completed the all the questions, please compare and circle the element that you considered having a bigger impact on the presidentiality of the helicopter.

- a) SHAPE OR AESTHETICS
b) SHAPE OR PROTOCOLS
c) AESTHETICS OR PROTOCOLS

Appendix D

EXCEL ANP TOOL: MACRO

D.1 Monte-Carlo Algorithm

```
Sub RUN_Monte_Carlo_OPS_MoE(NAME_SHEET_IN, NAME_SHEET_OUT, Num_Crit, Criteria, Crit_loc,
Num_sim, Result_loc, PRNT_Row)
    Dim Rand_Value As Integer
    Dim k As Integer
    Dim kk As Integer
    Dim i As Integer
    Dim RV_Criteria(20) As Double
    Dim RV_Criteria_1 As Double
    Dim RV_Criteria_2 As Double
    Dim RV_Criteria_3 As Double
    Dim RV_Criteria_1_Temp As Double
    Dim RV_Criteria_2_Temp As Double
    Dim RV_Criteria_3_Temp As Double
    Dim SUM_CRIT As Double
    Dim Rank_MoE As Integer
    kk = 1
    SUM_CRIT = 0
    Rand_Value = 1
    For i = 1 To Num_sim
        k = kk
        RV_Criteria(k) = Rnd * (Criteria(k, 2) - Criteria(k, 1)) + Criteria(k, 1)
        SUM_CRIT = SUM_CRIT + RV_Criteria(k)
        If k + 1 > Num_Crit Then
            k = 1
        Else
            k = k + 1
        End If
        For j = 1 To Num_Crit - 2
            RV_Criteria(k) = 1 - SUM_CRIT
            If RV_Criteria(k) > Criteria(k, 2) Then
                RV_Criteria(k) = Rnd * (Criteria(k, 2) - Criteria(k, 1)) + Criteria(k, 1)
                SUM_CRIT = SUM_CRIT + RV_Criteria(k)
            Else
                RV_Criteria(k) = Rnd * (RV_Criteria(k) - Criteria(k, 1)) + Criteria(k, 1)
                SUM_CRIT = SUM_CRIT + RV_Criteria(k)
            End If
            If k + 1 > Num_Crit Then
                k = 1
            Else
                k = k + 1
            End If
        Next j
    Next i
End Sub
```

```

        End If
    Next j
    RV_Criteria(k) = 1 - SUM_CRIT
    If RV_Criteria(k) > Criteria(k, 2) Then
        RV_Criteria(k) = Rnd * (Criteria(k, 2) - Criteria(k, 1)) + Criteria(k, 1)
        SUM_CRIT = SUM_CRIT + RV_Criteria(k)
    ElseIf RV_Criteria(k) - Criteria(k, 1) < 0 Then
        RV_Criteria(k) = 1 - SUM_CRIT
        SUM_CRIT = SUM_CRIT + RV_Criteria(k)
    Else
        RV_Criteria(k) = Rnd * (RV_Criteria(k) - Criteria(k, 1)) + Criteria(k, 1)
        SUM_CRIT = SUM_CRIT + RV_Criteria(k)
    End If
    For j = 1 To Num_Crit
        Worksheets(NAME_SHEET_IN).Cells(Crit_loc(1, 1) + j - 1, Crit_loc(1, 2)).Value = RV_Criteria(j)
        ' Worksheets(NAME_SHEET_OUT).Cells(PRNT_Row + i, 1 + j).Value = RV_Criteria(j)
    Next j
    If kk + 1 > Num_Crit Then
        kk = 1
    Else
        kk = kk + 1
    End If
    SUM_CRIT = 0
    'Worksheets(NAME_SHEET_IN).Cells(1, 10).Value = i
    Next i
End Sub

```

D.2 Matrix of Alternative and Compatibility Matrix Macro

The main program is called “*Compatibility_Click()*” and includes three sub-program:

1. Check_Comp: Check for incompatibility from the incompatibility matrix;
2. Expl_MoA: Check for the next compatible alternatives in the morphological matrix;
3. WRT_RESULTS: Store the Benefits, Costs and Risks normalized values.

```

Private Sub Compatibility_Click()
    Dim NAME_SHEET As String
    Dim NAME_SHEET_R As String
    Dim Select_Option As String
    Dim P_Type_Row As Integer
    Dim Slc_Col As Integer
    Dim Alter_Row_Start As Integer
    Dim Alter_Row_END As Integer
    Dim Alter_Col_Start As Integer
    Dim Alter_Col_END As Integer
    Dim Counter_Alter As Integer
    Dim Index_ROW(50) As Integer
    Dim Num_Alter(50) As Integer
    Dim Num_AlterComp(50) As Integer
    Dim Comp_Col(50, 50) As Integer
    Dim Length_OPT As Integer

```

```

Dim WRT_ROW As Integer
Dim WRT_COL As Integer
NAME_SHEET = "MoE_Alternatives_RUN"
NAME_SHEET_R = "MoE_EXPLORATION-BC"
Alter_Row_Start = 10
Alter_Row_END = 19
Alter_Col_Start = 6
Alter_Col_END = 13
P_Type_Row = 11
Slc_Col = 15
WRT_ROW = 2
WRT_COL = 1
Worksheets(NAME_SHEET).Range("O3:O43").ClearContents
Call Check_Comp
' Count Alternatives and Store in Array
ii = 0
For j = Alter_Row_Start To Alter_Row_END
    If Worksheets(NAME_SHEET).Cells(j, Alter_Col_Start).Interior.ColorIndex = 1 Then
        ' next row
    Else
        Counter_Alter = 0
        For i = Alter_Col_Start To Alter_Col_END
            If IsEmpty(Worksheets(NAME_SHEET).Cells(j, i).Value) = False Then
                Counter_Alter = Counter_Alter + 1
            End If
        Next i
        ' Store information
        Worksheets(NAME_SHEET).Cells(j, 14).Value = Counter_Alter
        ii = ii + 1
        Index_ROW(ii) = j
        Num_Alter(ii) = Counter_Alter
    End If
Next j
Length_OPT = ii
For i = 1 To 5
    Worksheets(NAME_SHEET).Range("O3:O43").ClearContents
    Select_Option = Worksheets(NAME_SHEET).Cells(Index_ROW(1), Alter_Col_Start + i - 1).Value
    Worksheets(NAME_SHEET).Cells(Index_ROW(1), Slc_Col).Value = Select_Option
    Call Check_Comp
    Num_AlterComp(2) = 0
    For j = 1 To Num_Alter(2)
        If Worksheets(NAME_SHEET).Cells(Index_ROW(2), Alter_Col_Start + j - 1).Interior.ColorIndex =
3 Then
            Else
                Num_AlterComp(2) = Num_AlterComp(2) + 1
                Comp_Col(2, Num_AlterComp(2)) = Alter_Col_Start + j - 1
            End If
        Next j
        For ii = 1 To Num_AlterComp(2)
            Call Expl_MoA(ii, 2, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)

```



```

Num_AlterComp(3) = 0
For j = 1 To Num_Alter(3)
    If Worksheets(NAME_SHEET).Cells(Index_ROW(3), Alter_Col_Start + j - 1).Interior.ColorIndex
= 3 Then
        Else
            Num_AlterComp(3) = Num_AlterComp(3) + 1
            Comp_Col(3, Num_AlterComp(3)) = Alter_Col_Start + j - 1
        End If
    Next j
For iii = 1 To Num_AlterComp(3)
    Call Expl_MoA(iii, 3, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)
    Num_AlterComp(4) = 0
    For j = 1 To Num_Alter(4)
        If Worksheets(NAME_SHEET).Cells(Index_ROW(4), Alter_Col_Start + j - 1).Interior.ColorIndex = 3 Then
            Else
                Num_AlterComp(4) = Num_AlterComp(4) + 1
                Comp_Col(4, Num_AlterComp(4)) = Alter_Col_Start + j - 1
            End If
        Next j
    For iv = 1 To Num_AlterComp(4)
        Call Expl_MoA(iv, 4, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)
        Num_AlterComp(5) = 0
        For j = 1 To Num_Alter(5)
            If Worksheets(NAME_SHEET).Cells(Index_ROW(5), Alter_Col_Start + j -
1).Interior.ColorIndex = 3 Then
                Else
                    Num_AlterComp(5) = Num_AlterComp(5) + 1
                    Comp_Col(5, Num_AlterComp(5)) = Alter_Col_Start + j - 1
                End If
            Next j
        For v = 1 To Num_AlterComp(5)
            Call Expl_MoA(v, 5, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)
            Num_AlterComp(6) = 0
            For j = 1 To Num_Alter(6)
                If Worksheets(NAME_SHEET).Cells(Index_ROW(6), Alter_Col_Start + j -
1).Interior.ColorIndex = 3 Then
                    Else
                        Num_AlterComp(6) = Num_AlterComp(6) + 1
                        Comp_Col(6, Num_AlterComp(6)) = Alter_Col_Start + j - 1
                    End If
                Next j
            If Num_AlterComp(6) > 0 Then
                For vi = 1 To Num_AlterComp(6)
                    Call Expl_MoA(vi, 6, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)
                    WRT_ROW = WRT_ROW + 1
                    Call WRT_RESULTS(NAME_SHEET, NAME_SHEET_R, Length_OPT, Index_ROW,
Slc_Col, WRT_ROW, WRT_COL)
                Next vi
            End If
        Next v
    Next iv
Next iii

```

```

Else
    WRT_ROW = WRT_ROW + 1
    Call WRT_RESULTS(NAME_SHEET, NAME_SHEET_R, Length_OPT, Index_ROW,
Slc_Col, WRT_ROW, WRT_COL)
End If
Next v
Next iv
Next iii
Next ii
Next i
End Sub
Sub Expl_MoA(ii, index, NAME_SHEET, Index_ROW, Slc_Col, Comp_Col)
' Select the next compatible option
Worksheets(NAME_SHEET).Range(Cells(Index_ROW(index), Slc_Col), Cells(Index_ROW(index) + 50, Slc_Col))
Call Check_Comp
If Worksheets(NAME_SHEET).Cells(Index_ROW(index), Comp_Col(index, ii)).Interior.ColorIndex = 3 Then
Else
    Select_Option = Worksheets(NAME_SHEET).Cells(Index_ROW(index), Comp_Col(index, ii)).Value
    Worksheets(NAME_SHEET).Cells(Index_ROW(index), Slc_Col).Value = Select_Option
    Call Check_Comp
End If
End Sub
Sub WRT_RESULTS(NAME_SHEET, NAME_SHEET_R, Length_OPT, Index_ROW, Slc_Col, WRT_ROW,
WRT_COL)
' ** Read the selection and write it in the results sheet **
For i = 1 To Length_OPT
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + i).Value
    = Worksheets(NAME_SHEET).Cells(Index_ROW(i), Slc_Col).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 1).Value
    = Worksheets("BENEFITS").Cells(23, 13).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 2).Value
    = Worksheets("BENEFITS").Cells(24, 13).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 3).Value
    = Worksheets("BENEFITS").Cells(25, 13).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 4).Value
    = Worksheets("BENEFITS").Cells(34, 13).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 5).Value
    = Worksheets("COSTS").Cells(15, 15).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 6).Value
    = Worksheets("COSTS").Cells(16, 15).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 7).Value
    = Worksheets("COSTS").Cells(23, 15).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 8).Value
    = Worksheets("RISKS").Cells(15, 15).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 9).Value
    = Worksheets("RISKS").Cells(16, 15).Value
Worksheets(NAME_SHEET_R).Cells(WRT_ROW, WRT_COL + Length_OPT + 10).Value
    = Worksheets("RISKS").Cells(23, 15).Value
Next i
End Sub

```

```

Sub Check_Comp()
' Actions -----
' (1) Check Compatibility
' (2) Put Compatibility in Red
Dim Num_Comp As Integer
Dim S_Row As Integer
Dim S_COL As Integer
Dim NAME_SHEET As String
Dim Selected_Value As String
Dim Comp_Matrix(50) As String
Dim Counter As Integer
Dim Counter2 As Integer
Dim Comp_Index(50) As Integer
S_Row = 3
S_COL = 15
S_Row_C = 4
S_COL_C = 2
NAME_SHEET = "MoE_Alternatives_RUN"
NAME_SHEET2 = "Compatibility_Matrix"
' Initiate the Color index
Worksheets(NAME_SHEET).Range("F3:M9").Interior.ColorIndex = 15
Worksheets(NAME_SHEET).Range("F11:M12").Interior.ColorIndex = 15
Worksheets(NAME_SHEET).Range("F14:M14").Interior.ColorIndex = 15
Worksheets(NAME_SHEET).Range("F16:M18").Interior.ColorIndex = 15
' List Comp-Matrix alternative
Num_Comp = 0
For i = 0 To 50
    If IsEmpty(Worksheets(NAME_SHEET2).Cells(S_Row_C + i, S_COL_C).Value) = False Then
        Num_Comp = Num_Comp + 1
        Comp_Matrix(Num_Comp) = Worksheets(NAME_SHEET2).Cells(S_Row_C + i, S_COL_C).Value
    End If
Next i
For i = 0 To 41
    Counter = 0
' Find incompatibilities
    If IsEmpty(Worksheets(NAME_SHEET).Cells(S_Row + i, S_COL).Value) = False Then
        Selected_Value = Worksheets(NAME_SHEET).Cells(S_Row + i, S_COL).Value
        'Search incomp. in Comp Matrix
        Do While Counter <= Num_Comp
            Counter = Counter + 1
            If Comp_Matrix(Counter) = Selected_Value Then
                Counter2 = 0
                For j = 1 To Num_Comp + 1 ' **** What are the incompatibilities ****
                    If Worksheets(NAME_SHEET2).Cells(S_Row_C + Counter - 1, S_COL_C + j -
1).Interior.ColorIndex = 3 Then
                        Counter2 = Counter2 + 1
                        Comp_Index(Counter2) = j - 1
                    End If
                Next j
                For j = 1 To Counter2 '**** Search Incompatibilities in MOA Alternative ****

```

```

        For ii = 3 To 41
            For jj = 6 To 13
                If Worksheets(NAME_SHEET).Cells(ii, jj).Value = Comp_Matrix(Comp_Index(jj))
Then
                    Worksheets(NAME_SHEET).Cells(ii, jj).Interior.ColorIndex = 3
                End If
            Next jj
        Next ii
    Next j
Exit Do
End If
Loop
End If
Next i
End Sub

```

Appendix E

DEFINITIONS

Design requirements:

- (IEEE, [80]): “**Design requirements:** A requirement that specifies or constrains the design of a system or system component. Contrast with: functional requirement; implementation requirement; interface requirement; performance requirement; physical requirement”
- (Jackson, [85]): “**Design requirements** are the attributes of the item needed to meet the performance requirements and constraints. These could include, for example, physical dimensions or power required.”
- (DoD, [43]): “**Design Requirements:** The “build to”, “code to”, and “buy to” requirements for products and “how to execute” requirements for processes expressed in technical data packages and technical manuals.”
- (INCOSE, [82]) “ **Design Requirements.** The “build to,” “code to,” and “buy to” requirements for products and “how to execute” requirements for processes. Design requirements are developed through synthesis of detailed design.”

Constraint requirements:

- (INCOSE, [83]) “**Design constraint:s**: The boundary conditions, externally or internally imposed, for the system of interest within which the organization must remain when the executing the processes during the concept and development stage.
- (IEEE, [81]) **Constraint:** “A statement that expresses measurable bounds for an element or function of the system. That is, a constraint is a factor that is imposed on the solution by force or compulsion and may limit or modify the design change.”
- (Jackson, [85]) **Constraint and specialty requirements:** “Suffice it to say that a constraint is any non-performance requirement; that is any requirement that cannot be traced to a function”

Performance requirements:

- (IEEE, [81]) “**Performance requirement**. A requirement that imposes conditions on a functional requirement; for example a requirement that specifies the speed, accuracy, or memory usage with which a given function must be performed”
- (Jackson, [85]) **Performance Requirements**: “A performance requirement is a measure of the extent to which a system performs a function. A basic concept is that all performance requirements are traceable to functions”
- (DoD, [43]) **Performance requirements**: “The extent to which a mission or function must be executed; generally measured in terms of quantity, quality, coverage, timeliness or readiness. During requirements analysis, performance (how well does it have to be done) requirements will be interactively developed across all identified functions based on system life cycle factors; and characterized in terms of the degree of certainty in their estimate, the degree of criticality to system success, and their relationship to other requirements.”
- (Young, [199]) “**Performance Requirements**: define how well the functional requirements must perform.”
- (INCOSE, [82]) Same as DoD.

Derived Requirements:

- (INCOSE, [83])“**Derived Requirements**: Detailed characteristics of the system of interest that typically are identified during the elicitation of stakeholder requirements, requirements analysis, trade studies or validation”
- (IEEE, [81])“**Derived requirement**: A requirement deduced or inferred from the collection and organization of requirements into a particular system configuration and solution”
- (Jackson, [85]) **Derived requirements**: “... depend on some feature of the solution to determine their values. For example, the value of engine thrust is a derived requirement determined from extensive trade-offs in the conceptual design process. ”
- (DoD, [43]) **Derived Requirements**: “Requirements that are implied or transformed from higher-level requirements. For example, a requirement for long range or high speed may result in a design requirement for low weight.”

- (Young, [199]) “**Derived requirements:** is one that is further refined from a higher-level requirement or a requirement that results from choosing a specific implementation or system element. In a sense all requirements are derived from the system need; thus the derived distinction tends to have little significance. However, many systems engineers distinguish between externally identified requirements and requirements that are derived under the control of the engineer.”

Functional requirements:

- (IEEE, [81]) “**Functional requirement.** A requirement that specifies a function that a system or system component must be able to perform.” STD 610
- (DoD, [43]) **Functional Requirement:** “The necessary task, action or activity that must be accomplish. Functional (what has to be done) requirements identified in requirements analysis will be used as the top-level functions for functional analysis.”
- (Young, [199])“**Functional Requirement:** Describe what the system or software must do. Sometimes called behavioral or operational requirements because they specify the input to the system, the outputs from the system, and behavioral relationships between them.”
- (INCOSE, [82]) “**Functional Requirement:** The necessary task, action, or activity that must be accomplished. The initial set of top-level functions are the eight primary system life-cycle functions. Top-level functions are identified by requirements analysis and subdivided by functional analysis.”

Non-Functional requirements:

- (Young, [199]) “**Non functional Requirements:** Specify system properties such as reliability and safety.”

Physical requirements:

- (IEEE, [81])“**Physical requirement.** A requirement that specifies a physical characteristic that a system or system component must possess; for example, material, shape, size, weight. ”STD 610

Interface requirements:

- (IEEE, [81])“**Interface requirement.** A requirement that specifies an external item with which a system or system component must interact, or that sets forth constraints on formats, timing, or other factors caused by such an interaction” STD 610

- (Young, [199])“**Interface requirements:** identifies physical and functional relationships among system elements and between system elements and the system environment.”
- (INCOSE, [82]) “**Interface Requirement:** The functional performance, electrical, environmental, human, and physical requirements and constraints that exist at a common boundary between two or more functions, system elements, configuration items, or system.”

Environmental requirements:

- (Young, [199])“**Environmental Requirements:** These are requirements that result from the physical setting and cultural conditions of the system development effort and the setting in which the system or software will be used.”

Implementation requirements:

- (IEEE, [81])“**Implementation requirement.** A requirement that specifies or constrains the coding or construction of a system or system component.” STD 610

Allocated requirements:

- (DoD, [43]) **Allocated requirements:** “A requirement that is establish by dividing or otherwise allocating a high-level requirement into multiple lower level requirements. Example: A 100-pound item that consists of two subsystems might result in a weight requirements of 70 pounds and 30 pounds for the two lower level items.”

Cost Requirements:

- (INCOSE, [82]) **Cost Requirements:** “The financial thresholds and objectives expressed in terms of design-to-cost targets, research, development, test and evaluation (RDT&E), operating and support costs, and flyaway, weapon system, unit procurement, program acquisition, and life-cycle costs.”

Customer requirements:

- (INCOSE, [82]) **Customer Requirements:** “Statements of fact and assumptions that define the expectations of the system in terms of mission or objectives, environment, constraints, and measures of effectiveness. These requirements are defined from a validated needs statement (Mission Needs Statement), from acquisition and program decision documentation, and from mission analyses of each of the primary system life-cycle functions.”

Schedule requirements:

- (INCOSE, [82]) **Schedule Requirements:** “Progress characteristics imposed in terms of operational capability, production and surge rates, production and repair cycle times, or other development time constraints.”

Time requirements:

- (INCOSE, [82]) **Time Requirements:** “Factors critical to achieving required functional capabilities that are dependent on accomplishing a given action within an opportunity window (e.g., a target is vulnerable to attack only for a certain amount of time). Frequently defined for mission success, safety, system resource availability, and production and manufacturing capabilities.”

REFERENCES

- [1] *ISO/IEC 15288:2002, Systems engineering - System life cycle processes*, 2002.
- [2] AEROVIRONMENT-HELIOS. <http://www.avinc.com/>, Online accessed May 2006.
- [3] AIRBUS A-318. <http://www.airbus.com>, Online accessed May 2006.
- [4] AKAO, Y., *Quality Function Deployment: Integrating Customer Requirements into Product Design*, Productivity Press: Cambridge, MA, 1990.
- [5] AKIYAMA, K., *Function analysis : systematic improvement of quality and performance*. Cambridge, Mass, 1991.
- [6] ALEXANDER, E. R., "Sensitivity analysis in complex decision models," *American Planning Association. Journal of the American Planning Association*, vol. 55, no. 3, pp. 323–, 1989.
- [7] ANNIS, C., "Central limit theorem." http://www.statisticalengineering.com/central_limit_theorem.htm, Online accessed January 2008.
- [8] ARMACOST, R. L. and HOSSEINI, J. C., "Identification of determinant attributes using the analytic hierarchy process," *Journal of the Academy of Marketing Science*, vol. Vol. 22, No 4, pp. 383–392, 1994.
- [9] ARMACOST, R., COMPOSITION, P., MULLENS, M., and SWART, W., "An ahp framework for prioritizing customer requirements in qfd: an industrialized housing application," *IIE Transactions*, vol. 26, pp. 72–9, July 1994.
- [10] AULL-HYDE, R., ERDOGAN, S., and DUKE, J. M., "An experiment on the consistency of aggregated comparison matrices in ahp," *European Journal of Operational Research*, vol. 171, pp. 290–295, May 2006.
- [11] BAKER, A. P., *The Role of Mission Requirements, Vehicle Attributes, Technologies and Uncertainty in Rotorcraft System Design*. PhD thesis, Georgia Institute of Technology, March 2002.
- [12] BAKER, ANDREW P; MAVRIS, D. N., "Assessing the simultaneous impact of requirements, vehicle characteristics, and technologies during aircraft design," in *39th AIAA Aerospace Sciences Meeting and Exhibit*, 2001.
- [13] BANDTE, O. and MAVRIS, D. N., "Multi-objective optimization using a joint probabilistic technique," *AIAA-2000-4758*, 2000.
- [14] BAR-YAM, Y., *Dynamics of Complex Systems*. Addison-Wesley, 1997.
- [15] BAUCHAU, O. A., "DYMORE User's Manual," <http://www.ae.gatech.edu/people/obauchau/>, vol. Georgia Institute of Technology, Online accessed Mai 2007.

- [16] BERTOLINI, M. and BEVILACQUA, M., "A combined goal programming-ahp approach to maintenance selection problem," *Reliability Engineering & System Safety*, vol. 91, pp. 839–848, July 2006.
- [17] BEZDEK, J. C., "Editorial: fuzzy models-what are they and why?," *Fuzzy Systems, IEEE Transactions on*, vol. 2, no. 1, pp. 43–, 1993.
- [18] BILLATOS, S. B. and GRIGELY, L. J., "Functional requirement mapping as a framework for concurrent engineering," *Concurrent Engineering*, vol. 1, pp. 171–178, 1993.
- [19] BODE, J. and FUNG, R. Y. K., "Cost engineering with quality function deployment," *Computers & Industrial Engineering*, vol. 35, pp. 587–590, Dec. 1998.
- [20] BOEING COMMERCIAL AIRPLANES (777). <http://www.boeing.com/commercial/777family/gallery>, Online accessed May 2006.
- [21] BOOZ, ALLEN, and HAMILTON, "New product management for the 1980s," tech. rep., Booz, Allen and Hamilton, Inc., New-York, 1982.
- [22] BOUCHEREAU, V. and ROWLANDS, H., "Methods and techniques to help quality function deployment (qfd)," *Benchmarking*, vol. 7, no. 1, pp. 8–, 2000.
- [23] CAGNO, E., CARON, F., and PEREGO, A., "Multi-criteria assessment of the probability of winning in the competitive bidding process," *International Journal of Project Management*, vol. 19, pp. 313–324, Aug. 2001.
- [24] CARDOSO, J. B., DE ALMEIDA, J. R., DIAS, J. M., and COELHO, P. G., "Structural reliability analysis using monte carlo simulation and neural networks," *Advances in Engineering Software*, vol. 39, pp. 505–513, June 2008.
- [25] CHAN, L.-K. and WU, M.-L., "Quality function deployment: A comprehensive review of its concepts and methods," *Quality Engineering*, vol. 15, no. 1, pp. 23–35, 2002.
- [26] CHAN, L.-K. and WU, M.-L., "Quality function deployment: a literature review," *European Journal of Operational Research*, vol. 143, pp. 463–97, Dec. 2002.
- [27] CHANG, C.-W., WU, C.-R., LIN, C.-T., and CHEN, H.-C., "An application of ahp and sensitivity analysis for selecting the best slicing machine," *Computers and Industrial Engineering*, vol. 52, pp. 296–307, mar 2007.
- [28] CHEN, H. and KOCAOGLU, D. F., "A sensitivity analysis algorithm for hierarchical decision models," *European Journal of Operational Research*, vol. 185, pp. 266–288, Feb. 2008.
- [29] CHEN, L.-H. and WENG, M.-C., "A fuzzy model for exploiting quality function deployment," *Mathematical and Computer Modelling*, vol. 38, pp. 559–570, Sept. 2003.
- [30] CHRISTENSEN, R., "Entropy minimax sourcebook," *Fundamentals of inductive reasoning, Entropy, Ltd., Lincoln, MA*, vol. 1-4, 1980.
- [31] COLUCCI, F., "Safety upgrades could delay new presidential helicopter." http://www.nationaldefensemagazine.org/issues/2005/Sep/Safety_Upgrades.htm, Online accessed January 2008.

- [32] COMPUTER SCIENCE AND MATHEMATICS-OAK RIDGE NATIONAL LABORATORY (CSM-ORNL), "Impact of Monte Carlo methods on scientific research." <http://www.csm.ornl.gov/ssi-expo/MChist.html>, Online accessed February 2008.
- [33] COX, T. H., NAGY, C. J., SKOOG, M. A., and SOMERS, I. A., "Civil uav capability assessment," NASA, http://www.nasa.gov/centers/dryden/pdf/111761main_UAV_Capabilities_Assessment.pdf, 2004, [Online accessed May 2007].
- [34] CRISTIANO, J. J., LIKER, J. K., and WHITE, III, C. C., "Customer-driven product development through quality function deployment in the u.s. and japan.," *Journal of Product Innovation Management*, vol. 17, no. 4, pp. 286–308, 2000.
- [35] CYSNEIROS, L., DO PRADO LEITE, J., and DE MELO SABAT NETO, J., "A framework for integrating non-functional requirements into conceptual models," *Requirements Engineering*, vol. 6, no. 2, pp. 97–115, 2001.
- [36] D., S. and C., M., "Modified vortex algorithm for low reynolds number, low aspect-ratio wings," *AIAA-2005-4608*, vol. Brigham Young University, 2005.
- [37] DABERKOW, D. and MAVRIS, D., "New approaches to conceptual and preliminary aircraft design: A comparative assessment of a neural network formulation and a response surface methodology," in *3rd World Aviation Congress and Exposition, AIAA-98-5509*, 1998.
- [38] DABERKOW, DEBORA D; MAVRIS, D. N., "An investigation of metamodeling techniques for complex systems design," in *9th AIAA/ISSMO Symposium and Exhibit on Multidisciplinary Analysis and Optimization, 4-6 Sept.*, 2002.
- [39] DELAURENTIS, D., KANG, T., LIM, C., MAVRIS, D., and SCHRAGE, D., "System-of-systems modeling for personal air vehicles," *AIAA-2002-05620*, 2002.
- [40] DELAURENTIS, D. A. and MAVRIS, D. N., "Uncertainty modeling and management in multidisciplinary analysis and synthesis," *AIAA*, 2000.
- [41] DELAURENTIS, D. A., MAVRIS, D. N., and SCHRAGE, D. P., "System synthesis in preliminary aircraft design using statistical methods," *20th International Council of the Aeronautical Sciences*, 1996.
- [42] DELUCA, A. and TERMINI, S., "A definition of a non-probabilistic entropy in the setting of fuzzy sets theory," *Inf. Control*, vol. 20, pp. 301–312, 1972.
- [43] Department of Defense, Systems Management College, *Systems Engineering Fundamentals*, Defense Acquisition University Press, 2001.
- [44] DICK, J. and CHARD, J., "The systems engineering sandwich: Combining requirements, models and design," in *Telelogic, White Paper*, 2004.
- [45] DIETER, G. E., *Engineering Design: A Materials and Processing Approach*. McGraw-Hill Higher Education, 3rd edition ed., 2000.
- [46] DRELA, M., *XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils*. Springer Verlag, 1989.

- [47] DUBOIS, D. and PRADE, H., *Fuzzy sets and systems : theory and applications*. New York : Academic Press, 1980.
- [48] DUFRESNE, S., JOHNSON, C. C., and MAVRIS, D., "A variable fidelity conceptual design environment for revolutionary unmanned aerial vehicles," *AIAA Journal of Aircraft*, Accepted Feb. 2008.
- [49] EARLY, J., PRICE, M., MAWHINNEY, P., CURRAN, R., and RAGHUNATHAN, S., "Framework tools for modelling and simulation in an integrated design environment," in *Collection of Technical Papers - AIAA 4th Aviation Technology, Integration, and Operations Forum, ATIO*, vol. 2, (Chicago, IL, United States), pp. 845–853, 2004.
- [50] FARRELL, C. E., "Adapting the systems engineering paradigm to system-of-systems programs," in *43rd AIAA Aerospace Sciences Meeting and Exhibit*, 2005.
- [51] FORMAN, E. H. and SELLY, M. A., *Decision by Objectives*. World Scientific Publishing, 2001.
- [52] FORREST, S., "Genetic algorithms," in *ACM Comput. Surv. (USA)*, vol. 28, (USA), pp. 77–80, ACM, Mar. 1996.
- [53] FORREST, S., "Genetic algorithms. principles of natural selection applied to computation," *Science*, vol. 261, no. 5123, pp. 872–878, 1993.
- [54] FUNG, R., POPPLEWELL, K., and XIE, J., "An intelligent hybrid system for customer requirements analysis and product attribute targets determination," *International Journal of Production Research*, vol. 36, pp. 13–34, Jan. 1998.
- [55] FUNG, R., TANG, J., TU, Y., and WANG, D., "Product design resources optimization using a non-linear fuzzy quality function deployment model," *International Journal of Production Research*, vol. 40, no. 3, pp. 585–599, 2002.
- [56] FUNG, R., TANG, J., TU, P. Y., and CHEN, Y., "Modelling of quality function deployment planning with resource allocation," *Research in Engineering Design*, vol. 14, pp. 247–55, Dec. 2003.
- [57] GERSHENSON, J. K. and STAUFFER, L. A., "The creation of a taxonomy for manufacturability design requirements," *Proc ASME Design Technical Conference - 7th Int. Conf. Design Theory and Methodology*, 1995.
- [58] GERSHENSON, J. K. and STAUFFER, L. A., "Taxonomy for design requirements from corporate customers," *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, vol. 11, no. 2, pp. 103–115, 1999.
- [59] GHODSYPOUR, S. H. and O'BRIEN, C., "A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming," *International Journal of Production Economics*, vol. 56-57, pp. 199–212, Sept. 1998.
- [60] GLOUDEMANS, J. R., DAVIS, P. C., and GELHAUSEN, P. A., "A rapid geometry modeler for conceptual aircraft," *AIAA Technical Paper*, 1996.

- [61] GREEN, L., ALEXANDROV, N., BROWN, S., CERRO, J., GUMBERT, C., SOROKACH, M., and BURG, C., "Decision support methods and tools," in *AIAA-2006-7028, 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2006.
- [62] H., L., W., C., and A., S., "Probabilistic sensitivity analysis methods for design under uncertainty," *AIAA Paper-2004-4589*.
- [63] HARKER, P. and VARGA, L., "The theory of ratio scale estimation: Saaty's analytic hierarchy process," *Management Science*, vol. 33, p. 1383, 1987.
- [64] HARMON, FREDERICK G; FRANK, A. A. C. J.-J., "Conceptual design and simulation of a small hybrid-electric unmanned aerial vehicle," *Journal of Aircraft. Sept.-Oct.*, vol. 43, no. 5, pp. 1490–1498, 2006.
- [65] HAUSER, J. R. and CLAUSING, D., "The house of quality," *Harvard Business Review*, vol. 66, no. 3, pp. 63–, 1988.
- [66] HAZELRIGG, G. A., "Validation of engineering design alternative selection methods," *Engineering Optimization*, vol. 35, no. 2, pp. 103 – 120, 2003.
- [67] HELLENDORF, H., "Design and development of fuzzy systems at Siemens R&D," in *Second IEEE International Conference on Fuzzy Systems*, 1993.
- [68] HELLENDORF, H. and THOMAS, C., "Defuzzification in fuzzy controllers," *Intell. Fuzzy Syst.*, vol. 1, pp. 109–123, 1993.
- [69] HELTON, J. C., JOHNSON, J. D., and OBERKAMPF, W. L., "An exploration of alternative approaches to the representation of uncertainty in model predictions," *Reliability Engineering & System Safety*, vol. 85, no. 1-3, pp. 39–71, 2004.
- [70] HELTON, J., JOHNSON, J., OBERKAMPF, W., and SALLABERRY, C., "Sensitivity analysis in conjunction with evidence theory representations of epistemic uncertainty," *Reliability Engineering & System Safety*, vol. 91, no. 10-11, pp. 1414–1434, 2006.
- [71] HELTON, J. C., "Uncertainty and sensitivity analysis techniques for use in performance assessment for radioactive waste disposal," *Reliability Engineering & System Safety*, vol. 42, no. 2-3, pp. 327–367, 1993.
- [72] HERRICK, K., "Development of the unmanned aerial vehicle market: forecasts and trends," *Air & Space Europe*, vol. 2, no. 2, pp. 25–27, 2000.
- [73] HISTORIC U.S. ARMY HELICOPTERS. <http://tri.army.mil/LC/CS/csa/aahist3.htm>, Online accessed September 2007.
- [74] HO, C.-T., *Strategic evaluation of emerging technologies in the semiconductor foundry industry (special case: semiconductor foundry industry in Taiwan)*. PhD thesis, Portland State University, 2004.
- [75] HO, W., "Integrated analytic hierarchy process and its applications - a literature review," *European Journal of Operational Research*, 2007.

- [76] HONOUR, E. C., "Requirements development: pre-recorded online course version 1.5," *University of Alabama at Huntsville, c. Honourcode, Inc.*, 2006.
- [77] HSIAO, S.-W., "Concurrent design method for developing a new product," *International Journal of Industrial Ergonomics*, vol. 29, pp. 41–55, Jan. 2002.
- [78] HSU, P.-F., WU, C.-R., and LI, Z.-R., "Optimizing resource-based allocation for senior citizen housing to ensure a competitive advantage using the analytic hierarchy process," *Building and Environment*, vol. 43, pp. 90–97, Jan. 2008.
- [79] HULL, ELIZABETH, C., JACKSON, K. J., and A. JEREMY, J. D., *Requirements engineering*. Springer-Verlag London, 2002.
- [80] IEEE, *Standard Glossary of Software Engineering Terminology*, 1990.
- [81] IEEE, *Guide for Developing System Requirements Specifications*, no. Std 1233, 1998.
- [82] INCOSE, *Systems Engineering Handbook, A "What To" Guide For All SE Practitioners*, no. TP-2003-016-02, 2004. Version 2a.
- [83] INCOSE, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, no. TP-2003-002-03 in Version 3, June 2006.
- [84] J., G. and X., D., "Sensitivity analysis with mixture of epistemic and aleatory uncertainties," *AIAA Journal*, vol. 45, 2007.
- [85] JACKSON, S., *Systems engineering for commercial aircraft*. Aldershot, England, 1997.
- [86] JORDAN, N. C., SALEH, J. H., and NEWMAN, D. J., "The extravehicular mobility unit: A review of environment, requirements, and design changes in the us spacesuit," *Acta Astronautica*, vol. 59, no. 12, pp. 1135–1145, 2006.
- [87] KAMARA, J. M. and J., A. C., "Client requirements processing for concurrent life-cycle design and construction," *Concurrent Engineering: Research and Applications*, 8 (2), pp 74-88, 2000.
- [88] KANO, N., SERAKU, N., TAKAHASHI, F., and TSJUI, S., "Attractive quality and must-be quality," *Hinshitsu: The Journal of the Japaneses Society for Quality Control*, pp. 39–48, 1984.
- [89] KAO, C. and LIU, S.-T., "Fractional programming approach to fuzzy weighted average," *Fuzzy Sets and Systems*, vol. 120, no. 2, pp. 435–444, 2001.
- [90] KARR, C. and GENTRY, E., "Fuzzy control of ph using genetic algorithms," *Fuzzy Systems, IEEE Transactions on*, vol. 1, no. 1, pp. 46–, 1993.
- [91] KARSAK, E. E., SOZER, S., and ALPTEKIN, S. E., "Product planning in quality function deployment using a combined analytic network process and goal programming approach," *Computers & Industrial Engineering*, vol. 44, pp. 171–190, Jan. 2003.
- [92] KIRBY, M. R., *A methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design*. PhD thesis, Georgia Institute of Technology, 2001.

- [93] KLIR, G. J., CLAIR, U. S., and YUAN, B., *Fuzzy Set Theory: Foundations and Applications*. Prentice-Hall, NJ, 1997.
- [94] KLIR, G. J. and YUAN, B., *Fuzzy sets and fuzzy logic : theory and applications*. Englewood Cliffs, N.J., 1995.
- [95] KWONG, C. K. and BAI, H., "A fuzzy ahp approach to the determination of importance weights of customer requirements in quality function deployment," *Journal of Intelligent Manufacturing*, vol. 13, pp. 367–377, Oct. 2002.
- [96] KWONG, C. K. and BAI, H., "Determining the importance weights for the customer requirements in qfd using a fuzzy ahp with an extent analysis approach," *IIE Transactions*, vol. 35, no. 7, pp. 619–626, 2003.
- [97] LAI, X., XIE, M., and TAN, T., "Optimizing product design using the kano model and qfd," in *2004 IEEE International Engineering Management Conference*, 2004.
- [98] LARRY DICKERSON, "UAV Market to Top 10 Billion over Next Decade, Forecast International, Press Release." <http://www.forecastinternational.com/press/>, online, accessed August 2007.
- [99] LEE, D. H. and PARK, D., "An efficient algorithm for fuzzy weighted average," *Fuzzy Sets and Systems*, vol. 87, pp. 39–45, Apr. 1997.
- [100] LEE, J. W. and KIM, S. H., "Using analytic network process and goal programming for interdependent information system project selection," *Computers & Operations Research*, vol. 27, pp. 367–382, Apr. 2000.
- [101] LEWE, J.-H., AHN, B.-H., DELAURENTIS, D. A., MAVRIS, D. N., and SCHRAGE, D. P., "An integrated decision-making method to identify design requirements through agent-based simulation for personal air vehicle system," *2002 AIAA Aircraft Technology, Integration, and Operations Forum*, no. AIAA 2002-5876, 2002.
- [102] LI, Y., *An Intelligent, Knowledge-based Multiple Criteria Decision Making Advisor for Systems Design*. PhD thesis, Georgia Institute of Technology, 2007.
- [103] LIU, H., CHEN, W., and SUDJANTO, A., "Relative entropy based method for probabilistic sensitivity analysis in engineering design," *Journal of Mechanical Design*, vol. 128, p. 326, 2006.
- [104] LIU, S.-T., "Rating design requirements in fuzzy quality function deployment via a mathematical programming approach," *International Journal of Production Research*, vol. 43, pp. 497–513, Feb. 2005.
- [105] LIU, X., "Parameterized defuzzification with maximum entropy weighting function—another view of the weighting function expectation method," *Mathematical and Computer Modelling*, 2006.
- [106] LOFGREN, M. and WITELL, L., "Kano's theory of attractive quality and packaging," *Quality Management Journal*, vol. 12, no. 3, pp. 7–20, 2005.

- [107] LOUCOPOULOS, P. and KARAKOSTAS, V., *System Requirements Engineering*. McGraw-Hill international series in software engineering, 1995.
- [108] M., K. and ZIONTS, S., eds., *Multiple Criteria Decision Making in the New Millennium - Paper " The Seven Pillars of the Analytic Hierarchy Process " by T.L. Saaty*, Lecture Notes in Economics and Mathematical Systems, 2000.
- [109] M, M. L. and J, S., "Analyzing organizational project alternatives for agile manufacturing processes: an analytical network approach," *International Journal of Production Research*, vol. 37, no. 2, pp. 241–261, 1999.
- [110] MADU, C. N., KUEI, C., and MADU, I. E., "A hierarchic metric approach for integration of green issues in manufacturing: a paper recycling application," *Journal of Environmental Management*, vol. 64, pp. 261–272, Mar. 2002.
- [111] MAIDEN, N., MAIDEN, N., and NCUBE, C., "Acquiring cots software selection requirements," in *Third International Conference on Requirements Engineering*, 1998.
- [112] MAMAT, N. and DANIEL, J., "Statistical analyses on time complexity and rank consistency between singular value decomposition and the duality approach in ahp: A case study of faculty member selection," *Mathematical and Computer Modelling*, 2007.
- [113] MANKINS, J. C., "Technology readiness levels, a white paper," 1995.
- [114] MARTIN, J., *Design of Man-Computer Dialogues*. Prentice-Hall, Inc, 1973.
- [115] MASON, W., "Software for aerodynamics and aircraft design." website, Virginia Tech, http://www.aoe.vt.edu/~mason/Mason_f/MRsoft.html, Online accessed April 2007.
- [116] MASUDA, T., "Hierarchical sensitivity analysis of priority used in analytic hierarchy process," *International Journal of Systems Science*, vol. 21, no. 2, pp. 415–427, 1990.
- [117] MATZLER, K. and HINTERHUBER, H. H., "How to make product development projects more successful by integrating kano's model of customer satisfaction into quality function deployment," *Technovation*, vol. 18, pp. 25–38, Jan. 1998.
- [118] MAVRIS, D. N., KIRBY, M., and QIU, S., "Technology impact forecasting for a high speed civil transport," *AIAA-1998-5547*.
- [119] MCCLURE, E. K., *An Evolving-Requirements TEchnology Assessment Process For Advanced Propulsion Concepts*. PhD thesis, Georgia Institute of Technology, 2006.
- [120] McDONALD, R., *Error Propagation and Metamodeling for a Fidelity Tradeoff Capability in Complex Systems Design*. PhD thesis, Georgia Institute of Technology, 2006.
- [121] MEADE, L. and PRESLEY, A., "R&d project selection using the analytic network process," *Engineering Management, IEEE Transactions on*, vol. 49, no. 1, pp. 59–66, 2002.
- [122] MERRIAM-WEBSTER ONLINE. <http://www.m-w.com/>, Online accessed November 2006.

- [123] MILLET, I. and SCHONER, B., "Incorporating negative values into the analytic hierarchy process," *Computers & Operations Research*, vol. 32, pp. 3163–3173, Dec. 2005.
- [124] MILLET, I. and WEDLEY, W. C., "Modelling risk and uncertainty with the analytic hierarchy process," *Journal of Multi-Criteria Decision Analysis*, vol. 11, pp. 97–107, Mar. 2002.
- [125] MIRANDA, L., ELLIOTT, R., and BAKER, W., "A generalized vortex lattice method for subsonic and supersonic flow applications," *NASA CR-2865*, 1977.
- [126] MOFFITT, B. A., BRADLEY, T. H., MAVRIS, D., and PAREKH, D. E., "Design space exploration of small-scale pem fuel cell long endurance aircraft," in *6th AIAA Aviation Technology, Integration, and Operations Conference*, vol. 1, pp. 14–29, 2006.
- [127] MYERS, R. and MONTGOMERY, D., *Response Surface Methodology: Process and Product Optimization Using Design Experiments*. John Wiley & Sons, Inc, 1995.
- [128] MYINT, S., "A framework of an intelligent quality function deployment (iqfd) for discrete assembly environment," *Computers & Industrial Engineering*, vol. 45, pp. 269–283, Aug. 2003.
- [129] NAM, T., *A Generalized Sizing Method for Revolutionary Concepts Under Probabilistic Design Constraints*. PhD thesis, Aerospace Dept, Georgia Institute of Technology, Atlanta, GA, 2007.
- [130] NASA, "Pathfinder Fact Sheet." <http://www.nasa.gov/centers/dryden/news/FactSheets/FS-034-DFRC.html>, cited July 6 2007.
- [131] NASA Procedural Requirements, NPR 7123.1A, *Systems Engineering Processes and Requirements*, 2007.
- [132] National Aeronautics and Space Administration, *NASA Systems Engineering Handbook*, SP610-S ed., 1995.
- [133] NEUFELD, D. J. and CHUNG, J., "Unmanned aerial vehicle conceptual design using a genetic algorithm, and data mining," in *InfoTech at Aerospace: Advancing Contemporary Aerospace Technologies and Their Integration*, vol. 3, pp. 1273–1297, AIAA, 2005.
- [134] NICKOL, C. L., GUYNN, M. D., KOHOUT, L. L., and OZOROSKI, T. A., "High altitude long endurance air vehicle analysis of alternatives and technology requirements development," in *45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada*, 2007.
- [135] NICKOL, C. L., GUYNN, M. D., KOHOUT, L. L., and OZOROSKI, T. A., "High altitude long endurance uav analysis of alternatives and technology requirements development," tech. rep., NASA/TP-2007-21486, 2007.
- [136] NOAA COSTAL SERVICES CENTER, "Historical Hurricane Tracks." <http://maps.csc.noaa.gov/hurricanes/viewer.html>, Online accessed September 2007.

- [137] NORTHROP GRUMMAN, NAVY UCAS-GLOBAL HAWK. <http://www.northropgrumman.com/unmanned/>, Online accessed May 2006.
- [138] OBERKAMPF, W. L., HELTON, J. C., JOSLYN, C. A., WOJTKIEWICZ, S. F., and FERSON, S., "Challenge problems: uncertainty in system response given uncertain parameters," *Reliability Engineering & System Safety*, vol. 85, no. 1-3, pp. 11–19, 2004.
- [139] OFFICE OF THE SECRETARY OF DEFENSE, ed., *Unmanned Aerial Vehicles Roadmap 2002-2027*, 2002.
- [140] ORCHARD, M N; NEWMAN, S. J., "The compound helicopter - why have we not succeeded before?," *Aeronautical Journal*, vol. 103, pp. 489–495, October 1999.
- [141] PARK, T. and KIM, K.-J., "Determination of an optimal set of design requirements using house of quality," *Journal of Operations Management*, vol. 16, no. 5, pp. 569–581, 1998.
- [142] PARTOVI, F. Y., "An analytical model of process choice in the chemical industry," *International Journal of Production Economics*, vol. 105, pp. 213–227, Jan. 2007.
- [143] PRICE, M., EARLY, J., CURRAN, R., BENARD, E., and RAGHUNATHAN, S., "Identifying interfaces in engineering systems," *AIAA Journal*, vol. 44, no. 3, pp. 529–540, 2006.
- [144] RAYMER, D. P., "Vehicle scaling laws for multidisciplinary optimization: Use of net design volume to improve optimization realism," *AIAA-2001-5246*, 2001.
- [145] RAYMER, D. P., *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astronautics, 1999.
- [146] RECHTIN, E., "The art of systems architecting," *IEEE Spectrum*, vol. 29, pp. 66–9, Oct. 1992.
- [147] RICHMAN, M., KENYON, J., and SEGA, R., "High speed and hypersonic science and technology," in *41st Joint Propulsion Conference and Exhibit*, AIAA-2005-4099.
- [148] RIZZI, A., "Potential flow around airfoil with boundary layer coupled one-way (pablo)," *The Royal Institute of Technology, Department of Aeronautics, Stockholm, Sweden*, vol. <http://www.nada.kth.se/~chris/pablo/pablo.html>, cited July 2007.
- [149] ROMEO, G. and FRULLA, G., "Heliplat: Aerodynamic and structural analysis of have solar powered platform," *AIAA-2002-3504*, 2002.
- [150] ROSENBLOOM, E. S., "A probabilistic interpretation of the final rankings in ahp," *European Journal of Operational Research*, vol. 96, pp. 371–378, Jan. 1997.
- [151] ROSS, T. J., *Fuzzy Logic: With Engineering Applications, Second Edition*. Wiley, 2004.
- [152] ROUNDS, K. S. and COOPER, J. S., "Development of product design requirements using taxonomies of environmental issues," *Research in Engineering Design*, vol. 13, no. 2, pp. 94–108, 2002.

- [153] SAADE, J., "A unifying approach to defuzzification and comparison of the outputs of fuzzy controllers," *Fuzzy Systems, IEEE Transactions on*, vol. 4, no. 3, pp. 227–237, 1996.
- [154] SAADE, J. and DIAB, H., "Defuzzification techniques for fuzzy controllers," *Systems, Man and Cybernetics, Part B, IEEE Transactions on*, vol. 30, no. 1, pp. 223–229, 2000.
- [155] SAATY, THOMAS, L. and VARGAS, LUIS, G., *Decision Making with The Analytic Network Process - Economics, Political, Social and Technological Applications with Benefits, Opportunities, Cost and Risks*. Springer, 2006.
- [156] SAATY, T. L., *The Analytic Hierarchy Process*. RWS Publications, 1996.
- [157] SAATY, T. L., *The Analytic Network Process, Second Edition*. RWS Publications, 2001.
- [158] SAATY, T. L., PENIWATI, K., and SHANG, J. S., "The analytic hierarchy process and human resource allocation: Half the story," *Mathematical and Computer Modelling*, vol. In Press, Accepted Manuscript, p. 1112, 2007.
- [159] SAATY, T. L., VARGAS, L. G., and DELLMANN, K., "The allocation of intangible resources: the analytic hierarchy process and linear programming," *Socio-Economic Planning Sciences*, vol. 37, pp. 169–184, Sept. 2003.
- [160] SAATY, T., "How to make a decision: The analytic hierarchy process.," *European Journal of Operational Research*, vol. 48, pp. 9–26, 1990.
- [161] SCHARL, JULIEN; MAVRIS, D., "Building parametric and probabilistic dynamic vehicle models using neural networks," 2001.
- [162] SCHRAGE, D. and MAVRIS, D., "Integrated Product/Process Design/Development (IPPD) Through Robust Design Simulation: The Key For Affordable Rotorcraft," *51st AHS Annual Forum*, 1995.
- [163] SOON YANG, Y., SEON JANG, B., and SEOG YEUN, Y., "QFD-based optimization using response surface method," *International Journal of Vehicle Design*, vol. 28, pp. 275–93, 2002.
- [164] STEUER, R. E. and NA, P., "Multiple criteria decision making combined with finance: A categorized bibliographic study," *European Journal of Operational Research*, vol. 150, pp. 496–515, Nov. 2003.
- [165] SUH, N. P., *The Principles of Design*. NY: Oxford University Press, 1990.
- [166] SULLIVAN, L., "Quality function deployment," *Qual. Prog.*, vol. 19(6), 39-50., 1986.
- [167] SUPER DECISIONS SOFTWARE FOR DECISIONS MAKING. <http://www.superdecisions.com/>, Online Accessed December 2007.
- [168] SYSTEM MODELING LANGUAGE (SYSML). <http://www.sysml.org>, Online accessed September 2007.

- [169] TAKAGI, H. and HAYASHI, I., "Nn-driven fuzzy reasoning," *Int. J. Approximate Reasoning*, vol. 5, pp. 191–212, 1991.
- [170] TAM, M. C. and TUMMALA, V. M. R., "An application of the ahp in vendor selection of a telecommunications system," *Omega*, vol. 29, pp. 171–182, Apr. 2001.
- [171] TANG, J., Y.K. FUNG, R., XU, B., and WANG, D., "A new approach to quality function deployment planning with financial consideration," *Computers & Operations Research*, vol. 29, pp. 1447–1463, Sept. 2002.
- [172] TELELOGIC DOORS. <http://www.telelogic.com/corp/products/doors/index.cfm>, Online accessed August 2006.
- [173] TEMPONI, C., YEN, J., and AMOS TIAO, W., "House of quality: A fuzzy logic-based requirements analysis," *European Journal of Operational Research*, vol. 117, pp. 340–354, Sept. 1999.
- [174] TEFAMARIAM, D. and LINDBERG, B., "Aggregate analysis of manufacturing systems using system dynamics and anp," *Computers & Industrial Engineering*, vol. 49, pp. 98–117, Aug. 2005.
- [175] TRIANTAPHYLLOU, E. and SANCHEZ, A., "A sensitivity analysis approach for some deterministic multi-criteria decision making methods," 1997.
- [176] TROCHIM, W. M., "Research methods knowledge based - types of data." <http://www.socialresearchmethods.net/kb/datatype.php>, Online accessed February 2008.
- [177] TUMMALA, V. M. R., CHIN, K. S., and HO, S. H., "Assessing success factors for implementing ce a case study in hong kong electronics industry by ahp," *International Journal of Production Economics*, vol. 49, pp. 265–283, May 1997.
- [178] ULLMAN, D. G., "A taxonomy for mechanical design," *Research in Engineering Design*, vol. V3, pp. 179–189, Sept. 1992.
- [179] UNIFIED MODELING LANGUAGE UML. <http://www.uml.org/>, Online accessed September 2007.
- [180] U.S. GENERAL ACCOUNTING OFFICE, "Best practices: Better matching of needs and resources will lead to better weapon system outcome," in *GAO-01-288*, 2001.
- [181] U.S. GENERAL ACCOUNTING OFFICE, "Defense acquisition - matching resources with requirements is key to the unmanned combat air vehicle program's success," in *GAO-03-598*, 2003.
- [182] U.S. GENERAL ACCOUNTING OFFICE, "Defense acquisitions: Assessment of selected weapon programs," in *GAO-07-406SP*, 2007.
- [183] VAIDYA, O. S. and KUMAR, S., "Dependency and its predictions for systems and its components," *International Journal of Quality & Reliability Management*, vol. 20, pp. 1096–1116, 2003.

- [184] VAN BROEKHOVEN, E. and DE BAETS, B., "A comparison of three methods for computing the center of gravity defuzzification," in *IEEE International Conference on Fuzzy Systems*, vol. 3, pp. 1537–1542 vol.3, 2004.
- [185] VAN DE WATER, H. and VAN PEET, H. P., "A decision support model based on the analytic hierarchy process for the make or buy decision in manufacturing," *Journal of Purchasing and Supply Management*, vol. In Press, Corrected Proof, p. 307, 2007.
- [186] VANEGAS, L. V. and LABIB, A. W., "Application of new fuzzy-weighted average (nfwa) method to engineering design evaluation," *International Journal of Production Research*, vol. 39, pp. 1147–1162, Apr. 2001.
- [187] VANEGAS, L. V. and LABIB, A. W., "A fuzzy quality function deployment (fqfd) model for deriving optimum targets," *International Journal of Production Research*, vol. 39, pp. 99–120, Jan. 2001.
- [188] VARGAS, L. G., "Comments on barzilai and lootsma why the multiplicative ahp is invalid: A practical counterexample," *Journal of Multi-Criteria Decision Analysis*, vol. 6, pp. 169–170, May 1997.
- [189] WANG, H. and XIE, M., "A comparative study of the prioritization matrix method and the analytic hierarchy process...," *Total Quality Management*, vol. 9, pp. 421–, Aug. 1998.
- [190] WANG, J., "Fuzzy outranking approach to prioritize design requirements in quality function deployment," *International Journal of Production Research*, vol. 37, pp. 899–916, Mar. 1999.
- [191] WASSERMAN, G. S., "On how to prioritize design requirements during the qfd planning process," *IIE Transactions*, vol. 25, no. 3, pp. 59–65, 1993.
- [192] WHITE, S. and EDWARDS, M., "A requirements taxonomy for specifying complex systems," in *First IEEE International Conference on Engineering of Complex Computer Systems*, pp. 373–376, 1995.
- [193] WIJNMALEN, D. J., "Analysis of benefits, opportunities, costs, and risks (bocr) with the ahp-anp: A critical validation," *Mathematical and Computer Modelling*, vol. 46, pp. 892–905, Oct. 2007.
- [194] WINEBRAKE, J. J. and CRESWICK, B. P., "The future of hydrogen fueling systems for transportation: An application of perspective-based scenario analysis using the analytic hierarchy process," *Technological Forecasting and Social Change*, vol. 70, pp. 359–384, May 2003.
- [195] WOMACK, J. and JONES, D. T., *Lean Thinking Second Edition*. 2003.
- [196] WRIGHT, H., CROOM, M., BRAUN, R., QUALLS, G., COSGROVE, P., and LEVINE, J., "Ares mission overview - capabilities and requirements of the robotic aerial platform," in *2nd AIAA "Unmanned Unlimited" Conf. and Workshop and Exhibit*, no. AIAA-2003-6577, 2003.

- [197] YAGER, R. and FILEV, D., "Template-based fuzzy systems modeling," *Intell. Fuzzy Syst.*, vol. 2, pp. 39–54, 1994.
- [198] YEH, J.-M., KRENG, B., and LIN, C., "A consensus approach for synthesizing the elements of comparison matrix in the analytic hierarchy process," *International Journal of Systems Science*, vol. 32, pp. 1353 – 1363, 2001.
- [199] YOUNG, R. R., *The Requirements Engineering Handbook*. Artech House, 2003.
- [200] YU, W., VOLOVOI, V. V., HODGES, D., and HONG, X., "Validation of the variational asymptotic beam sectional analysis," *AIAA Journal*, vol. Vol. 40, No. 10, pp. 2105–2112, 2002.
- [201] YURDAKUL, M., "Measuring long-term performance of a manufacturing firm using the analytic network process (anp) approach," *International Journal of Production Research*, vol. 41, no. 11, pp. 2501–2529, 2003.
- [202] ZADEH, L., "Fuzzy sets," *Inf. Control*, pp. 338–353, 1965.
- [203] ZADEH, L. A., "Quantitative fuzzy semantics," *Information Sciences*, vol. 3(2), pp. 159–176, 1971.
- [204] ZADEH, L. A., "The linguistic approach and its application to decision analysis," *In: Ho, Y.C. and S. K. Mitter, eds., Direction in Large Scale Systems. Plenum Press, New York*, pp. 339–370, 1976.
- [205] ZHANG, X., BODE, J., and REN, S., "Neural networks in quality function deployment," *Computers & Industrial Engineering*, vol. 31, no. 3-4, pp. 669–673, 1996.
- [206] ZIMMERMANN, H. J., *Fuzzy set theory and its applications, 2nd edition*. Kluwer Academic Publishers, Dordrecht, Germany, 1991.
- [207] ZWICKY, F. and WILSON, A. G., "New method of thought and procedure; contributions on symposium on methodologies," *Springer-Verlag*, 1967.

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